

Modeling in OWL 2 without Restrictions

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Abstract. The Semantic Web ontology language OWL 2 DL comes with a variety of language features that enable sophisticated and practically useful modeling. However, the use of these features has been severely restricted in order to retain decidability of the language. For example, OWL 2 DL does not allow a property to be both transitive and asymmetric, which would be desirable, e.g., for representing an ancestor relation. In this paper, we argue that the so-called “global restrictions” of OWL 2 DL preclude many useful forms of modeling, by providing a catalog of basic modeling patterns that would be available in OWL 2 DL if the global restrictions were discarded. We then report on the results of evaluating several state-of-the-art OWL 2 DL reasoners on problems that use combinations of features in a way that the global restrictions are violated. The systems turn out to rely heavily on the global restrictions and are thus largely incapable of coping with the modeling patterns. Next we show how off-the-shelf first-order logic theorem proving technology can be used to perform reasoning in the OWL 2 direct semantics, the semantics that underlies OWL 2 DL, but without requiring the global restrictions. Applying a naive proof-of-concept implementation of this approach to the test problems was successful in all cases. Based on our observations, we make suggestions for future lines of research on expressive description logic-style OWL reasoning.

Keywords: Semantic Web, Ontology, Modeling, OWL DL

1 Introduction

The Semantic Web ontology language OWL 2 DL [18,9,8] was standardized by the World Wide Web Consortium (W3C) in 2009 as a description logic-style formalism of high expressivity that still guarantees algorithmic decidability of core reasoning tasks such as ontology satisfiability and entailment checking. The language comes with a large number of language features that enable sophisticated modeling in many application domains. However, the use of these features has been restricted in a variety of ways in order to retain decidability of the language. For instance, via a collection of “*global restrictions*”, particular uses of certain features or a combination of these features are explicitly constrained. A class of features for which a large number of global restrictions have been defined are the so-called “*complex properties*”, that is, transitive properties and properties defined through property chain axioms. For example, OWL 2 DL allows

for declaring transitive properties as well as asymmetric properties, but does not allow a property to be both transitive and asymmetric, as would be natural for a property representing an ancestor relation or, more generally, any strict partial order. In this paper we analyze some of the practical ramifications of the global restrictions on complex properties. We argue that dropping the global restrictions would result in a large number of additional useful and relevant modeling options for knowledge representation with OWL 2. We believe that in many practical cases these advantages outweigh the theoretical advantages of decidability.

We start in Section 2 with a concise overview of OWL 2 DL and its global syntactic restrictions. In Section 3 we provide a catalog of basic modeling patterns that use complex properties in natural ways, but which are disallowed by the global restrictions. For all patterns, we give example use cases supporting their usefulness and practical relevance. For ontology authors, the catalog offers a large set of new useful modeling options and demonstrates the extended modeling potential available, in principle at least, through the OWL 2 standard. In the same way, the catalog allows for a better understanding of the actual limitations of modeling in OWL 2 DL due to the global restrictions. To our knowledge, no comparable catalog of patterns exists.

In Section 4 we report on the results of an evaluation of several state-of-the-art OWL 2 DL reasoners using test problems that are based on the modeling patterns. The evaluation results provide an understanding of what can be expected from existing reasoners when they are applied to input data that violates the global restrictions of OWL 2 DL. It has to be pointed out that such an investigation is meaningful, as the OWL 2 standard does *not* require OWL 2 DL reasoners to reject input beyond OWL 2 DL, but only specifies how such tools have to behave on legal OWL 2 DL input (see the definition of tool conformance for OWL 2 DL entailment checkers in [14]). It has already been noted that OWL 2 DL reasoners can frequently be applied to input data that is significantly beyond OWL 2 DL without producing processing errors, and that they sometimes produce the expected results [12]. Compared to that study, the test problems used in this paper intuitively appear to be more digestible to OWL 2 DL reasoners. They can be expressed in the OWL 2 structural specification [9] (of which OWL 2 DL is a syntactic fragment), which has a precise meaning under the OWL 2 direct semantics [8] – the semantics underlying OWL 2 DL. This gave rise to a hope that existing OWL 2 DL reasoners might be able to cope with our modeling patterns. However, the evaluation reveals that all the OWL 2 DL reasoners failed on all the modeling patterns.

In Section 5, as a possible path forward, we swiftly analyze the practical feasibility of using first-order logic (FOL) reasoning technology [11] to reason in OWL 2 DL without the global restrictions. To this end we translated our test problems into FOL theories in a straight-forward way, following the OWL 2 direct semantics [8] but without enforcing the global restrictions of OWL 2 DL. We then used off-the-shelf FOL theorem provers and model-finders on the translated test data. It turned out that this simple approach succeeded on all test cases.

Based on our observations, we make suggestions for future lines of research on expressive description logic-style OWL reasoning.

The paper includes appendices with additional technical information on which the paper is based. This information and the software developed for this paper is also available in the *supplementary material* at <http://www.fzi.de/downloads/ipe/schneid/srs12-complexrelations.zip>.

2 OWL 2 DL and Global Restrictions

2.1 OWL 2 DL

For space reasons, we refrain from repeating the structural specification of OWL 2 DL, and instead refer the reader to [9] for the complete details. Here we focus on the aspects important for our argument.

Recall that the basic modeling primitives in OWL are individuals, classes and properties, where the latter are interpreted by binary relations and strictly subdivided into data properties and object properties. Compared to its predecessor OWL 1, OWL 2 has been significantly extended by ways to describe characteristics and interdependencies on the object property level. In particular, `SubObjectPropertyOf` statements are allowed to take *property chains* as their first argument, as, e.g., in

```
SubObjectPropertyOf( ObjectPropertyChain( :hasParent :hasBrother ) :hasUncle )
```

expressing that somebody's parent's brother is the uncle of that somebody. In database terms one could say that the uncle relation subsumes the join of the parent relation with the brother relation. Another novel property-centric modeling feature is *property disjointness*, as, e.g., in

```
DisjointObjectProperties( :hasParent :hasUncle )
```

expressing that somebody's parent cannot be that somebody's uncle. Furthermore, OWL 2 allows for characterizing properties as functional, inverse-functional, reflexive, irreflexive, symmetric, asymmetric, or transitive as, e.g., in

```
TransitiveObjectProperty( :hasAncestor )
```

Recall further that the semantics of OWL 2 DL, called *direct semantics* [8] is established along the typical model-theoretic semantics in description logics [1], and is well-defined for any structurally specified OWL ontology even if it violates the global restrictions.

2.2 Global Restrictions

In order to ensure decidability despite the high expressivity of the diverse modeling features in OWL, the ways in which these features are allowed to interact had to be restricted. This led to the so-called *global restrictions* that an OWL 2 DL ontology has to satisfy. The name “global restrictions” comes from the fact that

satisfaction of these restrictions cannot be decided by looking at the ontology axioms in isolation but it depends on their interplay.

At the core of the restrictions is the notion of *simple* versus *complex* object properties. Roughly speaking, an object property is called complex, if it can be inferred from the join of two or more other object properties. For example, the above subproperty axiom renders the uncle property complex. The same holds for the ancestor property, since transitivity of a relation essentially means that the relation subsumes its own self-join.

The global restrictions severely constrain the ways in which complex properties can be used: according to the *restriction on simple properties*, complex properties are not allowed to occur in cardinality restrictions, self-restrictions, and property disjointness statements, nor is a complex property allowed to be characterized as functional, inverse-functional, irreflexive, or asymmetric.

Another severe restriction is on the co-occurrence of subproperty axioms. The rationale behind the rather technical *restriction on the property hierarchy* is to ensure that the set of property chains used to infer a complex property can be described as a regular language. Next to discarding certain subproperty axioms right away, this also prohibits the coexistence of certain such axioms.

Further restrictions apply to OWL 2 DL (referring to the use of blank nodes), but they are not of interest in this paper.

3 Modeling Patterns

This section presents a catalog of modeling patterns based on usage of OWL 2 language features in a way that violates the global restrictions of OWL 2 DL. The catalog consists of twelve modeling patterns, most of them representing different combinations of axioms defining complex properties, such as transitivity axioms, and language constructs that may only be used with simple properties, such as asymmetric property axioms; see Section 2 for a more detailed list of disallowed combinations of language constructs in OWL 2 DL. Each modeling pattern is described with a concrete example of a family relationship given in OWL 2 functional syntax, and is accompanied by an explanation of the conflicts with the OWL 2 DL specification. Additional use cases from other application areas provide evidence for the generality, usefulness, and relevance of the pattern.

We have to point out that the patterns were *not* taken from any existing OWL ontologies. As the patterns are explicitly disallowed in OWL 2 DL, and as many of the involved language features were introduced only recently as part of OWL 2, one cannot expect to find many of these patterns in real-world ontologies today. Rather, the goal is to demonstrate the drastic increase of modeling power in case the global restrictions of OWL 2 DL are discarded. Our motivations for choosing the modeling patterns were simplicity, plausibility, potential relevance, and generality.

We are aware that for some of the patterns it is possible to find a semantically equivalent reformulation that is valid in OWL 2 DL. However, the purpose of our pattern catalog is *not* to present semantic scenarios that cannot be expressed in

OWL 2 DL, but rather to offer to ontology authors a set of new modeling options that appear natural and simple using the features of OWL 2. We believe that for an ontology author, a complex or non-obvious reformulation of a pattern, in order to keep the ontology in OWL 2 DL, will often be unacceptable. Still, we consider work on such translations relevant as a means of “repairing” ontologies that use our modeling patterns, so that OWL 2 DL reasoners have a better chance of coping with such input (cf. the results in Section 4).

3.1 Strict Partial Orders

Strict partial orders are asymmetric transitive relations, such as the ancestor relationship between people:

```
TransitiveObjectProperty( :hasAncestor )
AsymmetricObjectProperty( :hasAncestor )
```

OWL 2 DL does not allow transitive properties to be asymmetric. Additional use cases include: comparison relations such as *greater-than*, part-whole relationships, and operational research tasks such as critical path analysis and supply chain management.

3.2 Characterized Composite Relations

Property chain axioms allow composite relations to be built, such as the uncle relation in terms of the parent and brother relations. Naturally, the uncle relation should be specified to be asymmetric:

```
SubObjectPropertyOf(
  ObjectPropertyChain( :hasParent :hasBrother )
  :hasUncle )
AsymmetricObjectProperty( :hasUncle )
```

OWL 2 DL does not allow composite properties to be asymmetric. Another use case is an asymmetric *n*th-order predecessor relation for a fixed number *n*, such as a grandparent defined as a parent’s parent (*n* = 2).

3.3 Disjoint Transitive Relation Pairs

Relations are often defined as pairs of complementary but mutually exclusive terms that are transitive, such as the ancestor and descendant relationships:

```
TransitiveObjectProperty( :hasAncestor )
TransitiveObjectProperty( :hasDescendant )
DisjointObjectProperties( :hasDescendant :hasAncestor )
```

OWL 2 DL does not allow disjointness of transitive properties. Another use case is disjoint pairs of comparison relations, such as *greater-than* and *smaller-than*. Another disallowed example of two disjoint relations of which only one is transitive is given by the SKOS semantic relations `skos:broaderTransitive` and `skos:related` [7] (S24, S27).

3.4 Disjoint Composite Relations

Relations composed using property chain axioms are often disjoint from one or more of the component relations. For example, when composing the uncle relation in terms of the parent and brother relations, then, realistically, all three relations are mutually disjoint:

```
SubObjectPropertyOf(
  ObjectPropertyChain( :hasParent :hasBrother )
  :hasUncle )
DisjointObjectProperties( :hasUncle :hasParent :hasBrother )
```

OWL 2 DL does not allow disjointness of composite properties. Another use case is an n th-order predecessor relation for a fixed number n , such as a grandparent defined as a parent's parent ($n = 2$), where the grandparent and parent relations are disjoint.

3.5 Lower-Bounded Transitive Relations

For some transitive relations it may be desirable to specify the minimum number of relationships per individual. For example, every person has at least two ancestors:

```
TransitiveObjectProperty( :hasAncestor )
SubClassOf(
  :Person
  ObjectMinCardinality( 2 :hasAncestor :Person ) )
```

OWL 2 DL does not allow cardinality restrictions on transitive properties. Other use cases are comparison relations over unbounded domains, such as *greater-than* for numbers, where for any given number n there are always numbers $m > n$.

3.6 Functional Composite Relations

For some relations composed by property chain axioms it may be desirable to define them to be functional. For example, every person has at most one living maternal grandfather, being the father of the person's mother:

```
SubObjectPropertyOf(
  ObjectPropertyChain( :hasMother :hasFather )
  :hasMaternalGrandfather )
FunctionalObjectProperty( :hasMaternalGrandfather )
```

OWL 2 DL does not allow composite properties to be functional. An additional use case is a part-ownership relation, in scenarios where items can only have a single owner and where the owner of an item also owns all parts of the item.

3.7 Propagated Relations

Some relationships between two individuals may “propagate” to two other individuals, due to a specific constellation of relationships that holds between all four individuals. For example, if Mary has mother Susan, and Bill has father John, where Susan and John are relatives, then Mary and Bill are also relatives. This can be expressed using property chain axioms:

```

SubObjectPropertyOf(
  ObjectPropertyChain(
    :hasMother
    :hasRelative
    ObjectInverseOf( :hasFather ) )
  :hasRelative )

```

This representation violates the regularity conditions for the property hierarchy of OWL 2 DL, as in chains of size 3 or larger, an inner property of the chain (:hasRelative in position 2) must not also occur as the composite property. An additional use case would be to characterize identical composite items, such as computers, to have identical corresponding components, such as the computer’s processors.

3.8 Interlaced Relation Definitions

Although there is no general method in OWL 2 to fully define a composite relation, one can sometimes encode a close characterization by interlacing two property chain axioms. For example, one can define an uncle as a cousin’s father, and a cousin as an uncle’s child:

```

SubObjectPropertyOf(
  ObjectPropertyChain( :hasCousin :hasFather )
  :hasUncle )
SubObjectPropertyOf(
  ObjectPropertyChain( :hasUncle ObjectInverseOf( :hasFather ) )
  :hasCousin )

```

Circular dependencies on the property hierarchy violate the regularity conditions of OWL 2 DL.

3.9 Scoped Equivalence Relations

Equivalence relations are transitive, symmetric and reflexive, but for reflexivity, a global scope is often not desirable, as it would entail that *everything* has the relationship. For example, being a relative to someone may be seen as an equivalence relation, provided that one accepts that everyone is a relative of himself. However, one would probably want to limit this relation to people, excluding, for instance, machines or ideas. OWL 2 supports this notion of a “locally-reflexive” property by self-restrictions:

```

SymmetricObjectProperty( :hasRelativeOrSelf )
TransitiveObjectProperty( :hasRelativeOrSelf )
EquivalentClasses( :Person ObjectHasSelf( :hasRelativeOrSelf ) )

```

OWL 2 DL does not allow self-restriction of transitive properties. Other use cases include the grouping of people according to some feature, such as having the same profession or nationality. SKOS specifies the mapping property `skos:exactMatch` as symmetric and transitive [7] (S44, S45), and it would be plausible and consistent with the SKOS standard to additionally make it locally reflexive to the class of SKOS concepts.

3.10 Quasi-Reflexive-Transitive Closures

The reflexive-transitive closure of a parent relation defined over the class of people is the smallest super relation that is both transitive and reflexive, where reflexivity is scoped to the class of people, i.e., a person’s ancestor or oneself. While it is not possible to represent the smallest such relation in OWL 2, a coarse approximation is possible using a self-restricted transitive super property:

```
SubObjectPropertyOf( :hasParent :hasAncestorOrSelf )
TransitiveObjectProperty( :hasAncestorOrSelf )
EquivalentClasses( :Person ObjectHasSelf( :hasAncestorOrSelf ) )
```

OWL 2 DL does not allow self-restriction of transitive properties. Another example is `skos:broaderTransitive`, the transitive extension of the SKOS semantic property `skos:broader` [7, S22,S24], for which it would be plausible and consistent with the SKOS standard to additionally make it locally reflexive to the class of SKOS concepts.

3.11 Homocyclic Relationships

Cyclic relationships constructed from one binary relation, such as the “loves” relation, may be of arbitrary size. For example, a person may love only himself or another person mutually, or there may be a cycle of unreturned love including several people. Each person in such a cycle can be represented as an instance of the class of “loved lovers” and, thus, instanceship in this class indicates that a person is part of such a cyclic relationship. Class instanceship can be expressed in terms of a self-restricted transitive super property of the loves property:

```
SubObjectPropertyOf( :loves :z )
TransitiveObjectProperty( :z )
SubClassOf( ObjectHasSelf( :z ) :LovedLover )
```

OWL 2 DL does not allow self-restriction of transitive properties. Another use case is chemical ring molecules of arbitrary size, where all bonds are of the same sort, such as Cycloalkanes.

3.12 Heterocyclic Relationships

Certain cyclic relations or coincidence relations can be composed from a set of different basic relations, such as the concept of a legitimate child, that is, a person with a father and a mother who are married. Occurrence of such relationships in a knowledge base can be indicated by instanceship in a class of legitimate children, modeled using a property chain axiom and a self-restriction:

```
SubObjectPropertyOf(
  ObjectPropertyChain(
    :hasMother
    :hasSpouse
    ObjectInverseOf( :hasFather ) )
  :z )
SubClassOf( ObjectHasSelf( :z ) :LegitimateChild )
```

OWL 2 DL does not allow self-restriction of composite properties. Another use case is circular molecules of a fixed size that are built from different sorts of bonds, such as Furan.

4 Evaluation of State-of-the-Art Semantic Web Reasoners

We now report on the results of evaluating several state-of-the-art OWL 2 DL reasoners using test problems based on the modeling patterns of Section 3. The focus was on finding out whether or not the reasoners can cope with the modeling patterns. As mentioned in Section 1, compliant OWL 2 DL reasoners are *not* required to reject input beyond the specification of OWL 2 DL, and experience shows that existing systems often do reason upon such input. Hence it is a legitimate question to ask how they behave on our modeling patterns. To give an answer, we checked whether the reasoners are able to recognize certain “obvious looking” logical conclusions from the modeling patterns according to the OWL 2 direct semantics. Reasoning performance was *not* considered an important aspect of our evaluation.

Test Data. We created a test suite consisting of one test case per modeling pattern. Each test case is built from two small ontologies, a premise and a conjecture. The premise covers the main example of the corresponding modeling pattern given in Section 3, typically extended by some additional assertions. The conjecture is a small set of assertions that follow logically from the premise. Both the premise and the conjecture ontology conform syntactically to the OWL 2 structural specification, and the conjecture is entailed from the premise according to the OWL 2 direct semantics. The test cases were designed to be “not too difficult to solve”, so that the OWL 2 DL reasoners do not fail due to high reasoning complexity. The complete test suite is described in full detail in Appendix A, and in the supplementary material.

Reasoners. We selected currently available reasoners that represent the state of the art in OWL 2 DL reasoning. We used OWL API 3.2.4 for parsing the test cases, and all reasoners were accessed via their respective OWL API reasoner interfaces.⁴

- **FaCT++ 1.5.3** (<http://owl.man.ac.uk/factplusplus>), created at the University of Manchester, England, is a tableaux-based OWL 2 DL reasoner.
- **HermiT 1.3.6** (<http://hermit-reasoner.com>), created at the University of Oxford, England, is a tableaux-based OWL 2 DL reasoner.
- **Pellet 2.3.0** (<http://clarkparsia.com/pellet>), created by Clark & Parsia, USA, is a tableaux-based OWL 2 DL reasoner.

Testing Environment. All tests were conducted on a mobile computer “Lenovo ThinkPad T410s” with an Intel® Core™ i5 M520 CPU (4 cores) at 2.4 GHz speed, 4 GB RAM, with Microsoft Windows 7 Professional (64-Bit) as the operating system. The CPU timeout for applying a reasoner to a test case was 300 seconds. The possible outcomes of the test runs are as follows:

- ‘+’: termination with correct result
- ‘-’: termination with wrong result
- ‘?’: processing error or timeout

⁴ OWL API homepage: <http://owlapi.sourceforge.net>

	01	02	03	04	05	06	07	08	09	10	11	12
<i>FaCT++</i>	?	?	?	?	?	?	?	?	?	?	?	?
<i>HermiT</i>	?	?	?	?	?	?	?	?	?	?	—	—
<i>Pellet</i>	—	—	—	—	—	—	—	—	—	—	?	—

Table 1. Entailment checking results for the OWL 2 DL reasoners using the twelve entailments of the “Complex Family Relations” test suite.

Results. Table 1 shows the outcomes of the evaluation. The details of the results can be found in Appendix B.1 and in the supplementary material. In summary, all reasoners failed on all test cases. *FaCT++* signalled errors on all test cases with error messages that in most cases correctly indicated which global restriction was violated. *HermiT* signaled ten errors with error messages that correctly identified the global restriction that was violated, while two test cases were wrongly recognized as non-entailments. *Pellet* signaled an error in only one case, and wrongly recognized all other test cases as non-entailments. In the majority of cases a warning message was found in the log file, which explained that Pellet had recognized a violated global restriction and chosen to ignore one or more of the premise axioms as a way to resolve the conflict. Without those axioms it was not possible to infer the conclusion ontologies. The CPU times taken by all the reasoners were below 20 ms for the majority of test cases, and *FaCT++* always returned after less than 10 ms. In order to find out whether the bad outcomes were at least partially due to the use of the OWL API, we compared the logical axioms and declarations after parsing the test case data with those in the original test cases, and found no differences. This indicates that the reasoners are mainly responsible for the outcomes themselves.

Discussion. These results strongly indicate that today’s OWL 2 DL reasoners cannot reliably be used with input that violates the global restrictions of OWL 2 DL. Note that this does not mean to accuse these reasoners of malfunctioning, they just do not go the extra mile beyond their specified input language and hence are not suitable for reasoning in the extended language that we are targeting.⁵ Apparently two different strategies are used by the reasoners in this situation: *FaCT++* and *HermiT* rigidly reject the input, while *Pellet* processes the input with some of the conflicting axioms being ignored, which may lead to missing or wrong results. For users who want to apply some of the modeling patterns introduced earlier in this paper, none of these strategies is acceptable. Therefore, a different strategy that does not have these problems is needed. We will propose and evaluate one such strategy in the next section.

⁵ For someone familiar with the methods used in state-of-the-art OWL reasoners this fact does not come as a big surprise. For instance, the restriction on the property hierarchy is a crucial prerequisite for preprocessing the ontology ahead of the actual core reasoning procedures.

5 First-Order-Based OWL 2 Reasoning

Based on the observation that the semantics of OWL 2 DL, i.e., the OWL 2 direct semantics, is based on standard first-order logic (FOL), this section describes how off-the-shelf FOL reasoning technology can be used for reasoning over the modeling patterns given in Section 3.

5.1 First-Order Logic and Automated Theorem Proving

Automated Theorem Proving (ATP) for classical first-order logic is a well established field, with a solid foundation of theory that provides the basis for the many high-performance ATP systems that have been developed [11]. ATP for classical first-order logic is semi-decidable, i.e., given axioms and a provable conjecture it is possible to build an ATP system that, in principle, is guaranteed to prove that the conjecture is a theorem logically entailed by the axioms. On the flip-side, given a satisfiable set of first-order formulae, it is not possible in general to build an ATP system that can confirm their satisfiability, e.g., by finding a model of the formulae. In practice, many ATP systems sacrifice theoretical completeness of theorem proving for better practical completeness over established work profiles, and the theoretical incompleteness of model finding systems has not prevented them from being practically useful in many ways. ATP has been successfully used in a broad range of application domains, such as mathematics, hardware and software verification, social sciences, agents and planning, and, as is relevant to this paper, reasoning for the Semantic Web. In concrete daily practice, many ATP systems use the TPTP language [16] for problem input and solution output, and the TPTP language has been used for this work.

5.2 FOL-Based OWL 2 Reasoning Approach

The reasoning approach consists of two steps. Firstly, OWL 2 ontologies are translated into TPTP formulae following the OWL 2 direct semantics. Secondly, FOL reasoning systems are applied to the TPTP formulae. The translation of OWL 2 ontologies into TPTP closely follows the definitions in the OWL 2 direct semantics specification [8], which give semantic meaning to all OWL 2 axioms and expressions using a FOL/set-theoretical model theory. For instance, the example OWL 2 axiom from Section 2.1

```
SubObjectPropertyOf( ObjectPropertyChain( :hasParent :hasBrother ) :hasUncle )
```

has the following meaning according to Table 6 of the OWL 2 direct semantics:

$$\forall y_0, y_1, y_2 : (y_0, y_1) \in \text{:hasParent}^{OP} \wedge (y_1, y_2) \in \text{:hasBrother}^{OP} \Rightarrow (y_0, y_2) \in \text{:hasUncle}^{OP}$$

and is mapped into the following TPTP formula:

```
! [Y0,Y1,Y2] : ( ( uri_hasParent(Y0,Y1) & uri_hasBrother(Y1,Y2) ) => uri_hasUncle(Y0,Y2) )
```

An implementation of the translation is available as an executable tool in the supplementary material.

For satisfiability checking, the ontology to be checked is translated into a TPTP axiom formula. For entailment checking, the premise ontology is translated into a TPTP axiom formula, and the conclusion ontology is translated into a TPTP conjecture formula. The TPTP formulae are then given to FOL reasoning systems, typically a theorem prover and a model-finder, ideally applied to the input data in parallel. The theorem prover will try to detect that the input is unsatisfiable or an entailment, while the model-finder will try to detect that the input is satisfiable or a non-entailment.

This idea has been used in the past for reasoning experiments in OWL 1 DL [17]. Those results are now largely outdated and are not very representative, as they use only a single FOL theorem prover (Vampire) in a very old version, and no FOL model-finders were used for model-finding tasks. Moreover, the reported experiments were restricted to input data strictly in the scope of OWL 1 DL, while most of our modeling scenarios are only possible in OWL 2 and they are all outside the scope of OWL 2 DL. Recently there have also been experiments applying FOL reasoning to OWL 2 Full [12]. However, the approach described there does not apply to our work, as OWL 2 Full uses a different semantics to OWL 2 DL, and as the approach used there differs strongly from our approach by the use of a FOL axiomatisation of the semantics of OWL 2 Full and by translating input ontologies according to their RDF graph representation instead of their representation and semantic meaning as OWL constructs.

5.3 Evaluation

We now present the results of evaluating the FOL-based reasoning approach using several state-of-the-art FOL reasoners. As test data, we used the “Complex Family Relations” that was used for the evaluation of the OWL 2 DL reasoners in Section 4. The test cases were translated into TPTP formulae as described in Section 5.2, and given to the FOL reasoners for entailment checking. We also applied the FOL reasoners to the (provably satisfiable) premise ontologies of the test cases to check whether FOL reasoners can be used for the generally undecidable task of satisfiability checking in the unrestricted OWL 2 direct semantics.

The Reasoners. The following FOL theorem provers and model finders were used in the evaluation, using their current stable version at the time of writing:

- **E 1.5** (<http://www.e prover.org>) [13], created at the Technische Universität München, Germany, is a purely equational theorem prover, using a saturation algorithm that implements an instance of the superposition calculus with negative literal selection.
- **iProver 0.9.2** (<http://www.cs.man.ac.uk/~korovink/iprover>) [6], created at the University of Manchester, England, is based on the Inst-Gen calculus. It combines ordered resolution with ground reasoning.

- **SPASS 3.5** (<http://www.spass-prover.org>) [19], created at the Max-Planck-Institut für Informatik, Germany, is a saturation based theorem prover, employing superposition, sorts and splitting.
- **Vampire 2.5** (<http://www.vprover.org>) [10], created at the University of Manchester, England, is a theorem prover implementing the calculi of ordered binary resolution, superposition, and the Inst-gen calculus. Strategy scheduling is used to apply different combinations of techniques.
- **Paradox 4.0** (<http://www.cse.chalmers.se/~koen/code/>) [5], created at Chalmers University of Technology, Sweden, is a finite model finder, based on MACE-style flattening and instantiation, and the use of a SAT solver to solve the resulting problem.
- **DarwinFM 1.4.5** (<http://goedel.cs.uiowa.edu/Darwin>) [2], created at NICTA, Australia, and the University of Iowa, USA, is a finite model finder in the spirit of Paradox. For each domain size the problem is transformed into an equisatisfiable function-free clause set, which is decided by the Darwin prover [3].

Testing Environment. We used the TPTP reasoning service [15], available at <http://tptp.org/cgi-bin/SystemOnTPTP>, which offers online access to all the FOL reasoners. Readers may use this service to repeat the experiments conducted here. The underlying machine has 4 Intel® Xeon® 5140 CPUs at 2.33 GHz speed, 4 GB RAM (1 GB per CPU), with Linux 2.6.31 as the operating system. The possible outcomes were the same as described in Section 4. The CPU timeout was again set to 300 seconds.

Results. Tables 2 and 3 show the outcomes of the entailment checking and satisfiability checking evaluation, respectively. The details of the results can be found in the Appendices B.2 and B.3 and in the supplementary material. No wrong results were produced by any reasoner. All theorem provers (listed in the upper part of the tables) succeeded on all entailment tests, and all model finders (listed in the lower part of the tables) succeeded on all satisfiability tests. Hence, any pair of a theorem prover and a model finder applied in parallel would succeed on all the test cases. The reasoning times were always below 50 ms and in many cases below 10 ms, so they are comparable with those of the OWL 2 DL reasoners reported in Section 4. While these times are of limited explanatory power (given the small sizes of the test data), we can at least see that the FOL reasoners had no difficulty with this input data. It is also interesting to observe that all the theorem provers succeeded on most of the satisfiability tests, and all the model finders succeeded on most of the entailment tests. In fact, each model finder terminated on the majority of entailment test cases in less than 10 ms. The few cases of “unknown” outcomes in the tables were timeouts, i.e., no explicit error was ever reported.

5.4 Discussion

Research in description logic-style OWL reasoning has focused largely on creating feature-rich but decidable ontology languages, and reasoners that closely

	01	02	03	04	05	06	07	08	09	10	11	12
E	+	+	+	+	+	+	+	+	+	+	+	+
iProver	+	+	+	+	+	+	+	+	+	+	+	+
SPASS	+	+	+	+	+	+	+	+	+	+	+	+
Vampire	+	+	+	+	+	+	+	+	+	+	+	+
DarwinFM	+	+	+	+	?	+	+	+	+	+	+	+
Paradox	+	+	+	+	?	+	+	+	+	+	+	+

Table 2. Entailment checking results for the FOL reasoning systems using the twelve entailments of the “Complex Family Relations” test suite.

	01	02	03	04	05	06	07	08	09	10	11	12
E	+	+	+	+	?	+	+	+	+	+	+	+
iProver	+	+	+	+	+	+	+	+	+	+	+	+
SPASS	+	+	+	+	?	+	+	+	+	+	+	+
Vampire	+	+	+	+	?	+	+	+	+	+	+	+
DarwinFM	+	+	+	+	+	+	+	+	+	+	+	+
Paradox	+	+	+	+	+	+	+	+	+	+	+	+

Table 3. Satisfiability checking results for the FOL reasoning systems using the twelve premise ontologies of the “Complex Family Relations” test suite.

conform to the specification of the language and its usage. We have seen that this approach prohibits many practically useful modeling options, and that current OWL 2 DL reasoners are not able to go the extra mile and cope with such modeling options. We have also seen that these scenarios can be dealt with in a straightforward manner using FOL reasoning technology. FOL reasoning is undecidable, and it can probably not compete in performance and scalability with highly specialized description-logic-style OWL 2 DL reasoning on OWL 2 DL input. However, due to the compatibility of the semantics of OWL 2 DL and FOL, it will be possible to build hybrid systems from both kinds of reasoning systems. An inexpensive syntax check can be used to direct all valid OWL 2 DL input to an OWL 2 DL system, and input beyond OWL 2 DL to a FOL system.

The hybrid approach is fully complete on valid OWL 2 DL input, and complete with regard to entailment and inconsistency detection even outside OWL 2 DL, due to the *semi*-decidability of FOL reasoning. Completeness is further guaranteed for non-entailment and satisfiability detection in cases where a finite model exists. Regarding the remaining undecidable task of detecting satisfiability if no finite model exists, it will be necessary to investigate how frequently this case occurs in practice (it did not occur in any of our tests). Existing FOL reasoners will sometimes be able to succeed even in these cases, and tools such as Infinox [4] can be used to detect cases where no finite model exists, and one can

also try to develop specialized incomplete methods for finding infinite models to cover the practically most relevant scenarios of unrestricted OWL reasoning.

While the performance of a hybrid system applied to legal OWL 2 DL input would presumably be comparable with that of existing OWL 2 DL reasoners (the only difference is an additional syntax check), we would also want its performance to be acceptable outside the borders of OWL 2 DL. Our results from the small test problems in our evaluation do not allow us to make a general statement about performance. As mentioned in Section 5.1, ATP has been successfully applied to a broad range of real-world applications, so one might be confident about their performance in OWL reasoning as well. However, current FOL reasoners do not provide any specific support for OWL features, and our proof-of-concept system did not include any OWL-specific optimizations. It will therefore be necessary to apply this approach to larger test cases, and spend considerable research effort developing optimization methods for FOL-based OWL reasoning.

The hybrid reasoning strategy will allow description-logic researchers to continue their successful work of further optimizing reasoning performance in the case of fully compliant OWL 2 DL input, while new research possibilities will open up concerning the optimization of ATP-based OWL reasoning, even including extensions beyond the current limits of OWL, such as Boolean property expressions, or rule-style extensions (SWRL, RIF+OWL DL combinations).

6 Conclusion

In this paper we have shown that many useful and relevant modeling options were available in OWL 2 DL if the global restrictions on complex properties would be relinquished. We have presented a catalog of twelve basic useful modeling patterns that are in the scope of the unrestricted structural specification and the direct semantics of OWL 2 but are beyond the scope of OWL 2 DL, including strict partial orders and different forms of circular relationships. Although the OWL 2 DL standard does not prevent compliant reasoners from processing such input, all the state-of-the-art OWL 2 DL reasoners that we tested were unable to cope with these modeling scenarios.

The use of generic FOL reasoning technology led to fully satisfying results on our test data. We therefore suggest building loosely coupled hybrid OWL 2 reasoners from traditional tableaux-based systems and generic FOL systems, to cover a wider range of input without sacrificing the completeness guarantees and high efficiency of today's OWL 2 DL reasoners on legal OWL 2 DL input. As further research tasks we propose investigating the optimization potential of FOL reasoning for unrestricted OWL, and determining the most relevant use cases of non-finite model finding for OWL reasoning, and the development of specialized reasoning methods for them.

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References

1. Baader, F., McGuinness, D.L., Nardi, D., Patel-Schneider, P.F. (eds.): The Description Logic Handbook: Theory, Implementation, and Applications. Cambridge University Press, Cambridge (2003)
2. Baumgartner, P., Fuchs, A., de Nivelle, H., Tinelli, C.: Computing Finite Models by Reduction to Function-Free Clause Logic. In: Ahrendt, W., Baumgartner, P., de Nivelle, H. (eds.) Proceedings of the 3rd Workshop on Disproving - Non-Theorems, Non-Validity, Non-Provability, 3rd International Joint Conference on Automated Reasoning (2006)
3. Baumgartner, P., Fuchs, A., Tinelli, C.: Implementing the Model Evolution Calculus. *International Journal on Artificial Intelligence Tools* 15(1), 21–52 (2006)
4. Claessen, K., Lilliestrom, A.: Automated Inference of Finite Unsatisfiability. In: Schmidt, R. (ed.) Proceedings of the 22nd International Conference on Automated Deduction. pp. 388–403. No. 5663 in *Lecture Notes in Artificial Intelligence*, Springer-Verlag (2009)
5. Claessen, K., Sörensson, N.: New Techniques that Improve MACE-style Finite Model Finding. In: Baumgartner, P., Fermueller, C. (eds.) Proceedings of the CADE-19 Workshop: Model Computation - Principles, Algorithms, Applications (2003)
6. Korovin, K.: iProver - An Instantiation-Based Theorem Prover for First-order Logic (System Description). In: Baumgartner, P., Armando, A., Gilles, D. (eds.) Proceedings of the 4th International Joint Conference on Automated Reasoning. pp. 292–298. No. 5195 in *Lecture Notes in Artificial Intelligence* (2008)
7. Miles, A., Bechhofer, S. (eds.): SKOS Simple Knowledge Organization System Reference. W3C Recommendation (18 August 2009), access: <http://www.w3.org/TR/skos-reference/>
8. Motik, B., Patel-Schneider, P.F., Grau, B.C. (eds.): OWL 2 Web Ontology Language: Direct Semantics. W3C Recommendation (27 October 2009), access: <http://www.w3.org/TR/owl2-direct-semantics/>
9. Motik, B., Patel-Schneider, P.F., Parsia, B. (eds.): OWL 2 Web Ontology Language: Structural Specification and Functional-Style Syntax. W3C Recommendation (27 October 2009), access: <http://www.w3.org/TR/owl2-syntax/>
10. Riazanov, A., Voronkov, A.: The Design and Implementation of Vampire. *AI Communications* 15(2-3), 91–110 (2002)
11. Robinson, A., Voronkov, A.: Handbook of Automated Reasoning. Elsevier Science (2001)
12. Schneider, M., Sutcliffe, G.: Reasoning in the OWL 2 Full Ontology Language using First-Order Automated Theorem Proving. In: Proc. CADE 23. LNAI, vol. 6803, pp. 446–460 (2011), extended version at <http://arxiv.org/abs/1108.0155>
13. Schulz, S.: E: A Brainiac Theorem Prover. *AI Communications* 15(2-3), 111–126 (2002)
14. Smith, M., Horrocks, I., Krötzsch, M., Glimm, B. (eds.): OWL 2 Web Ontology Language: Conformance. W3C Recommendation (27 October 2009), access: <http://www.w3.org/TR/owl2-conformance/>

15. Sutcliffe, G.: The TPTP World - Infrastructure for Automated Reasoning. In: Clarke, E., Voronkov, A. (eds.) *Proceedings of the 16th International Conference on Logic for Programming Artificial Intelligence and Reasoning*, pp. 1–12. No. 6355 in *Lecture Notes in Artificial Intelligence*, Springer-Verlag (2010)
16. Sutcliffe, G.: The TPTP Problem Library and Associated Infrastructure. The FOF and CNF Parts, v3.5.0. *J. Automated Reasoning* 43(4), 337–362 (2009), current version at <http://tptp.org/TPTP/TR/TPTPTR.shtml>
17. Tsarkov, D., Riazanov, A., Bechhofer, S., Horrocks, I.: Using Vampire to Reason with OWL. In: *Proceedings of the Third International Semantic Web Conference (ISWC 2004)*. LNCS, vol. 3298, pp. 471–485. Springer (2004)
18. W3C OWL Working Group (ed.): *OWL 2 Web Ontology Language: Document Overview*. W3C Recommendation (27 October 2009), access: <http://www.w3.org/TR/owl2-overview/>
19. Weidenbach, C., Fietzke, A., Kumar, R., Suda, M., Wischniewski, P., Dimova, D.: SPASS Version 3.5. In: Schmidt, R. (ed.) *Proceedings of the 22nd International Conference on Automated Deduction*, pp. 140–145. No. 5663 in *Lecture Notes in Artificial Intelligence*, Springer-Verlag (2009)

A Test Suite “Complex Family Relations”

This is the “Complex Family Relations” test suite for OWL 2 reasoning. The test suite consists of a set of test cases that are compliant with the OWL 2 Structural Specification (<http://www.w3.org/TR/owl2-syntax/>) and have a precise meaning under the OWL 2 Direct Semantics (<http://www.w3.org/TR/owl2-direct-semantics/>), but do not conform to the narrower specification of OWL 2 DL (see Chapter 3 of the OWL 2 Structural Specification). Each test case is an example for a particular modeling pattern, in which some of the global syntactic restrictions of OWL 2 DL are hurt (see Chapter 11 of the OWL 2 Structural Specification). Every test case consists of a premise and conclusion ontology, where the premise ontology is syntactically invalid with regard to OWL 2 DL and the conclusion ontology is logically entailed from the premise ontology under the OWL 2 Direct Semantics. The test cases represent certain family relationships and follow the style of the well-known “Families” ontology, which is used in the OWL 2 Primer for demonstrating the language features of OWL 2 (see Chapter 13 of the OWL 2 Primer, available at <http://www.w3.org/TR/owl2-primer/>). The syntax for all ontologies is the OWL 2 Functional Syntax, as defined in the OWL 2 Structural Specification document. The test cases are also available in electronical form in the supplementary material.

A.1 Test Case “01AsymmetricTransitive”

The ancestor relationship can be represented as a strict partial order, that is, an asymmetric transitive property: If Mary has ancestor Bill who has ancestor John, then Mary has John as her ancestor, but John cannot have Mary as his ancestor. OWL 2 DL does not allow transitive properties to be asymmetric.

Modeling Pattern: Strict Partial Orders, Section 3.1.

Premise:

```
Prefix( : = <http://example.org#> )
Ontology(
  Declaration( NamedIndividual( :Mary ) )
  Declaration( NamedIndividual( :Bill ) )
  Declaration( NamedIndividual( :John ) )
  Declaration( ObjectProperty( :hasAncestor ) )
  TransitiveObjectProperty( :hasAncestor )
  AsymmetricObjectProperty( :hasAncestor )
  ObjectPropertyAssertion( :hasAncestor :Mary :Bill )
  ObjectPropertyAssertion( :hasAncestor :Bill :John )
)
```

Conclusion:

```
Prefix( : = <http://example.org#> )
Ontology(
  Declaration( NamedIndividual( :Mary ) )
  Declaration( NamedIndividual( :John ) )
  Declaration( ObjectProperty( :hasAncestor ) )
  ObjectPropertyAssertion( :hasAncestor :Mary :John )
  NegativeObjectPropertyAssertion( :hasAncestor :John :Mary )
)
```

A.2 Test Case “02AsymmetricChained”

The uncle relationship can be composed from the parent and brother properties using a property chain axiom. Naturally, the uncle relation would further be specified to be asymmetric: If Mary has parent Bill who has brother John, then Mary has John as her uncle, but John cannot have Mary as his uncle. OWL 2 DL does not allow composite properties to be asymmetric.

Modeling Pattern: Characterized Composite Relations, Section 3.2.

Premise:

```
Prefix( : = <http://example.org#> )
Ontology(
  Declaration( NamedIndividual( :Mary ) )
  Declaration( NamedIndividual( :Bill ) )
  Declaration( NamedIndividual( :John ) )
  Declaration( ObjectProperty( :hasParent ) )
  Declaration( ObjectProperty( :hasBrother ) )
  Declaration( ObjectProperty( :hasUncle ) )
  SubObjectPropertyOf(
    ObjectPropertyChain( :hasParent :hasBrother )
    :hasUncle )
  AsymmetricObjectProperty( :hasUncle )
  ObjectPropertyAssertion( :hasParent :Mary :Bill )
  ObjectPropertyAssertion( :hasBrother :Bill :John )
)
```

Conclusion:

```
Prefix( : = <http://example.org#> )
Ontology(
  Declaration( NamedIndividual( :Mary ) )
  Declaration( NamedIndividual( :John ) )
  Declaration( ObjectProperty( :hasUncle ) )
  ObjectPropertyAssertion( :hasUncle :Mary :John )
  NegativeObjectPropertyAssertion( :hasUncle :John :Mary )
)
```

A.3 Test Case “03DisjointTransitive”

The pair of ancestor and descendant relationships can be represented as mutually disjoint transitive properties: If Mary has ancestor Bill, and Bill has ancestor John, then Mary has John as her ancestor, but not as her descendant. OWL 2 DL does not allow to put disjointness axioms on transitive properties.

Modeling Pattern: Disjoint Transitive Relation Pairs, Section 3.3.

Premise:

```
Prefix( : = <http://example.org#> )
Ontology(
  Declaration( NamedIndividual( :Mary ) )
  Declaration( NamedIndividual( :Bill ) )
  Declaration( NamedIndividual( :John ) )
  Declaration( ObjectProperty( :hasAncestor ) )
  Declaration( ObjectProperty( :hasDescendant ) )
  TransitiveObjectProperty( :hasAncestor )
  TransitiveObjectProperty( :hasDescendant )
  DisjointObjectProperties( :hasDescendant :hasAncestor )
  ObjectPropertyAssertion( :hasAncestor :Mary :Bill )
  ObjectPropertyAssertion( :hasAncestor :Bill :John )
)
```

Conclusion:

```

Prefix( : = <http://example.org#> )
Ontology(
  Declaration( NamedIndividual( :Mary ) )
  Declaration( NamedIndividual( :John ) )
  Declaration( ObjectProperty( :hasAncestor ) )
  Declaration( ObjectProperty( :hasDescendant ) )
  ObjectPropertyAssertion( :hasAncestor :Mary :John )
  NegativeObjectPropertyAssertion( :hasDescendant :Mary :John )
)

```

A.4 Test Case “04DisjointChained”

The uncle relationship can be composed from the parent and brother properties using a property chain axiom. Naturally, all these properties would further be specified to be mutually disjoint: If Mary has parent Bill, and Bill has brother John, then Mary has John as her uncle, but cannot have John as her parent or brother. OWL 2 DL does not allow to put disjointness axioms on composite properties.

Modeling Pattern: Disjoint Composite Relations, Section 3.4.

Premise:

```

Prefix( : = <http://example.org#> )
Ontology(
  Declaration( NamedIndividual( :Mary ) )
  Declaration( NamedIndividual( :Bill ) )
  Declaration( NamedIndividual( :John ) )
  Declaration( ObjectProperty( :hasUncle ) )
  Declaration( ObjectProperty( :hasParent ) )
  Declaration( ObjectProperty( :hasBrother ) )
  SubObjectPropertyOf(
    ObjectPropertyChain( :hasParent :hasBrother )
    :hasUncle )
  DisjointObjectProperties( :hasUncle :hasParent :hasBrother )
  ObjectPropertyAssertion( :hasParent :Mary :Bill )
  ObjectPropertyAssertion( :hasBrother :Bill :John )
)

```

Conclusion:

```

Prefix( : = <http://example.org#> )
Ontology(
  Declaration( NamedIndividual( :Mary ) )
  Declaration( NamedIndividual( :John ) )
  Declaration( ObjectProperty( :hasUncle ) )
  Declaration( ObjectProperty( :hasParent ) )
  Declaration( ObjectProperty( :hasBrother ) )
  ObjectPropertyAssertion( :hasUncle :Mary :John )
  NegativeObjectPropertyAssertion( :hasParent :Mary :John )
  NegativeObjectPropertyAssertion( :hasBrother :Mary :John )
)

```

A.5 Test Case “05NumberrestrictedTransitive”

The ancestor relationship between persons can be understood to be a transitive property such that every person has at least two ancestors: If Mary is a person, then there are persons X and Y, such that Mary has ancestor X, person X

has ancestor Y, and Mary has ancestor Y. This can be represented by using a minimum cardinality restriction on a transitive property. OWL 2 DL does not allow to put cardinality restrictions on transitive properties.

Modeling Pattern: Lower-Bounded Transitive Relations, Section 3.5.

Premise:

```
Prefix( : = <http://example.org#> )
Ontology(
  Declaration( NamedIndividual( :Mary ) )
  Declaration( Class( :Person ) )
  Declaration( ObjectProperty( :hasAncestor ) )
  TransitiveObjectProperty( :hasAncestor )
  SubClassOf(
    :Person
    ObjectMinCardinality( 2 :hasAncestor :Person ) )
  ClassAssertion( :Person :Mary )
)
```

Conclusion:

```
Prefix( : = <http://example.org#> )
Ontology(
  Declaration( NamedIndividual( :Mary ) )
  Declaration( Class( :Person ) )
  Declaration( ObjectProperty( :hasAncestor ) )
  ClassAssertion( :Person _:x )
  ClassAssertion( :Person _:y )
  ObjectPropertyAssertion( :hasAncestor :Mary _:x )
  ObjectPropertyAssertion( :hasAncestor _:x _:y )
  ObjectPropertyAssertion( :hasAncestor :Mary _:y )
)
```

A.6 Test Case “06NumberrestrictedChained”

The maternal grandfather relationship can be composed from the mother and father properties using a property chain axiom, where the composed property would naturally be functional: If Mary has mother Susan, and Susan has the two fathers Jim and James, then Mary has Jim and James as their maternal grandfathers, where Jim is identical to James. OWL 2 DL does not allow composite properties to be functional.

Modeling Pattern: Functional Composite Relations, Section 3.6.

Premise:

```
Prefix( : = <http://example.org#> )
Ontology(
  Declaration( NamedIndividual( :Mary ) )
  Declaration( NamedIndividual( :Susan ) )
  Declaration( NamedIndividual( :Jim ) )
  Declaration( NamedIndividual( :James ) )
  Declaration( ObjectProperty( :hasMother ) )
  Declaration( ObjectProperty( :hasFather ) )
  Declaration( ObjectProperty( :hasMaternalGrandfather ) )
  SubObjectPropertyOf(
    ObjectPropertyChain( :hasMother :hasFather )
    :hasMaternalGrandfather )
  FunctionalObjectProperty( :hasMaternalGrandfather )
  ObjectPropertyAssertion( :hasMother :Mary :Susan )
  ObjectPropertyAssertion( :hasFather :Susan :Jim )
  ObjectPropertyAssertion( :hasFather :Susan :James )
)
```

Conclusion:

```

Prefix( : = <http://example.org#> )
Ontology(
  Declaration( NamedIndividual( :Mary ) )
  Declaration( NamedIndividual( :Jim ) )
  Declaration( NamedIndividual( :James ) )
  Declaration( ObjectProperty( :hasMaternalGrandfather ) )
  ObjectPropertyAssertion( :hasMaternalGrandfather :Mary :Jim )
  SameIndividual( :Jim :James )
)

```

A.7 Test Case “07NonregularSingleChained”

The relatives relationship between two persons Susan and John can propagate to two other persons Mary and Bill, for instance if Mary has Susan as her mother and Bill has John as his father. This can be expressed using property chain axioms by composing the relative property from the mother, the relative, and the inverse of the father property. This representation hurts the regularity conditions for the property hierarchy of OWL 2 DL, as in chains of size 3, an inner property of the chain must not also occur as the composite property.

Modeling Pattern: Propagated Relations, Section 3.7.

Premise:

```

Prefix( : = <http://example.org#> )
Ontology(
  Declaration( NamedIndividual( :Mary ) )
  Declaration( NamedIndividual( :Bill ) )
  Declaration( NamedIndividual( :John ) )
  Declaration( NamedIndividual( :Susan ) )
  Declaration( ObjectProperty( :hasMother ) )
  Declaration( ObjectProperty( :hasFather ) )
  Declaration( ObjectProperty( :hasRelative ) )
  SubObjectPropertyOf(
    ObjectPropertyChain(
      :hasMother
      :hasRelative
      ObjectInverseOf( :hasFather ) )
    :hasRelative )
  ObjectPropertyAssertion( :hasMother :Mary :Susan )
  ObjectPropertyAssertion( :hasFather :Bill :John )
  ObjectPropertyAssertion( :hasRelative :Susan :John )
)

```

Conclusion:

```

Prefix( : = <http://example.org#> )
Ontology(
  Declaration( NamedIndividual( :Mary ) )
  Declaration( NamedIndividual( :Bill ) )
  Declaration( ObjectProperty( :hasRelative ) )
  ObjectPropertyAssertion( :hasRelative :Mary :Bill )
)

```

A.8 Test Case “08NonregularMultiChained”

Two interlaced property chain axioms can be used to closer characterize the uncle relationship, by composing the uncle relationship from the cousin and

father relationships, and the cousin relationship from the uncle and the inverse of the father relationships. Hence, if Mary has cousin Bill and father John, and Bill has father Jim and uncle John, then Mary has Jim as her uncle and Bill has Mary as his cousin. The use of circular dependencies on the property hierarchy break the regularity conditions of OWL 2 DL.

Modeling Pattern: Interlaced Relation Definitions, Section 3.8.

Premise:

```
Prefix( : = <http://example.org#> )
Ontology(
  Declaration( NamedIndividual( :Mary ) )
  Declaration( NamedIndividual( :Bill ) )
  Declaration( NamedIndividual( :John ) )
  Declaration( NamedIndividual( :Jim ) )
  Declaration( ObjectProperty( :hasFather ) )
  Declaration( ObjectProperty( :hasUncle ) )
  Declaration( ObjectProperty( :hasCousin ) )
  SubObjectPropertyOf(
    ObjectPropertyChain( :hasCousin :hasFather )
    :hasUncle )
  SubObjectPropertyOf(
    ObjectPropertyChain( :hasUncle ObjectInverseOf( :hasFather ) )
    :hasCousin )
  ObjectPropertyAssertion( :hasCousin :Mary :Bill )
  ObjectPropertyAssertion( :hasFather :Mary :John )
  ObjectPropertyAssertion( :hasFather :Bill :Jim )
  ObjectPropertyAssertion( :hasUncle :Bill :John )
)
```

Conclusion:

```
Prefix( : = <http://example.org#> )
Ontology(
  Declaration( NamedIndividual( :Mary ) )
  Declaration( NamedIndividual( :Jim ) )
  Declaration( NamedIndividual( :Bill ) )
  Declaration( ObjectProperty( :hasUncle ) )
  Declaration( ObjectProperty( :hasCousin ) )
  ObjectPropertyAssertion( :hasUncle :Mary :Jim )
  ObjectPropertyAssertion( :hasCousin :Bill :Mary )
)
```

A.9 Test Case “09ScopedEquivalence”

Having some other person or oneself as a relative can be modeled as a scoped equivalence relation, for which application is limited to the class of persons, i.e., as a symmetric transitive property with a self-restriction over the Person class. Hence, if Mary has relatives John and Jim and Bill is another person, then John has relatives Mary and Jim, and Mary and Bill each have themselves as relatives. However, if C3PO is not a person, then C3PO cannot have itself as a relative. OWL 2 DL does not allow for self-restrictions on transitive properties.

Modeling Pattern: Scoped Equivalence Relations, Section 3.9.

Premise:

```

Prefix( : = <http://example.org#> )
Ontology(
  Declaration( NamedIndividual( :Mary ) )
  Declaration( NamedIndividual( :Bill ) )
  Declaration( NamedIndividual( :John ) )
  Declaration( NamedIndividual( :Jim ) )
  Declaration( NamedIndividual( :C3PO ) )
  Declaration( Class( :Person ) )
  Declaration( ObjectProperty( :hasRelativeOrSelf ) )
  SymmetricObjectProperty( :hasRelativeOrSelf )
  TransitiveObjectProperty( :hasRelativeOrSelf )
  EquivalentClasses( :Person ObjectHasSelf( :hasRelativeOrSelf ) )
  ClassAssertion( :Person :Mary )
  ClassAssertion( :Person :Bill )
  ClassAssertion( :Person :John )
  ClassAssertion( :Person :Jim )
  ClassAssertion( ObjectComplementOf( :Person ) :C3PO )
  ObjectPropertyAssertion( :hasRelativeOrSelf :Mary :John )
  ObjectPropertyAssertion( :hasRelativeOrSelf :Mary :Jim )
)

```

Conclusion:

```

Prefix( : = <http://example.org#> )
Ontology(
  Declaration( NamedIndividual( :Mary ) )
  Declaration( NamedIndividual( :Bill ) )
  Declaration( NamedIndividual( :John ) )
  Declaration( NamedIndividual( :Jim ) )
  Declaration( NamedIndividual( :C3PO ) )
  Declaration( ObjectProperty( :hasRelativeOrSelf ) )
  ObjectPropertyAssertion( :hasRelativeOrSelf :John :Mary )
  ObjectPropertyAssertion( :hasRelativeOrSelf :John :Jim )
  ObjectPropertyAssertion( :hasRelativeOrSelf :Mary :Mary )
  ObjectPropertyAssertion( :hasRelativeOrSelf :Bill :Bill )
  NegativeObjectPropertyAssertion( :hasRelativeOrSelf :C3PO :C3PO )
)

```

A.10 Test Case “10ReflexiveTransitive”

The reflexive-transitive closure of the parent relationship between persons is the extended ancestor relationship that is also reflexive, while being scoped to persons. It can be coarsely approximated by a transitive super property of the parent property that is used in a self-restriction over the class of persons. Hence, if Mary has parent Bill who has parent John, then Mary is in the extended ancestor relationship with Bill, John and herself. However, if C3PO is not a person, then C3PO cannot be in an ancestor relationship with itself. OWL 2 DL does not allow for self-restrictions on transitive properties.

Modeling Pattern: Quasi-Reflexive-Transitive Closures, Section 3.10.

Premise:

```

Prefix( : = <http://example.org#> )
Ontology(
  Declaration( NamedIndividual( :Mary ) )
  Declaration( NamedIndividual( :Bill ) )
  Declaration( NamedIndividual( :John ) )
  Declaration( NamedIndividual( :C3PO ) )
  Declaration( Class( :Person ) )
  Declaration( ObjectProperty( :hasParent ) )
  Declaration( ObjectProperty( :hasAncestorOrSelf ) )
)

```



```

SubObjectPropertyOf( :hasParent :hasAncestorOrSelf )
TransitiveObjectProperty( :hasAncestorOrSelf )
EquivalentClasses( :Person ObjectHasSelf( :hasAncestorOrSelf ) )
ClassAssertion( :Person :Mary )
ClassAssertion( :Person :Bill )
ClassAssertion( :Person :John )
ClassAssertion( ObjectComplementOf( :Person ) :C3P0 )
ObjectPropertyAssertion( :hasParent :Mary :Bill )
ObjectPropertyAssertion( :hasParent :Bill :John )
)

```

Conclusion:

```

Prefix( : = <http://example.org#> )
Ontology(
  Declaration( NamedIndividual( :Mary ) )
  Declaration( NamedIndividual( :Bill ) )
  Declaration( NamedIndividual( :John ) )
  Declaration( NamedIndividual( :C3P0 ) )
  Declaration( ObjectProperty( :hasAncestorOrSelf ) )
  ObjectPropertyAssertion( :hasAncestorOrSelf :Mary :Mary )
  ObjectPropertyAssertion( :hasAncestorOrSelf :Mary :Bill )
  ObjectPropertyAssertion( :hasAncestorOrSelf :Mary :John )
  NegativeObjectPropertyAssertion( :hasAncestorOrSelf :C3P0 :C3P0 )
)

```

A.11 Test Case “11CyclicSingleRelation”

Binary relationships, such as loving someone, may be used to build circular relationships and the relationship cycles may be of arbitrary size: Jack may only love himself, John and Joan may love each other, and Mary may love Bill, who loves Susan, who loves Jim, who again loves Mary. Persons being in such a loves-relationship cycle can be seen as instances of the class of loved lovers. In our examples, all listed persons would be instances of this class. Class instanceship can be expressed in terms of a self-restricted transitive super property of the loves property, but this is not allowed in OWL 2 DL.

Modeling Pattern: Homocyclic Relationships, Section 3.11.

Premise:

```

Prefix( : = <http://example.org#> )
Ontology(
  Declaration( NamedIndividual( :Jack ) )
  Declaration( NamedIndividual( :John ) )
  Declaration( NamedIndividual( :Joan ) )
  Declaration( NamedIndividual( :Mary ) )
  Declaration( NamedIndividual( :Bill ) )
  Declaration( NamedIndividual( :Susan ) )
  Declaration( NamedIndividual( :Jim ) )
  Declaration( Class( :LovedLover ) )
  Declaration( ObjectProperty( :loves ) )
  Declaration( ObjectProperty( :z ) )
  SubObjectPropertyOf( :loves :z )
  TransitiveObjectProperty( :z )
  SubClassOf( ObjectHasSelf( :z ) :LovedLover )
  ObjectPropertyAssertion( :loves :Jack :Jack )
  ObjectPropertyAssertion( :loves :John :Joan )
  ObjectPropertyAssertion( :loves :Joan :John )
  ObjectPropertyAssertion( :loves :Mary :Bill )
  ObjectPropertyAssertion( :loves :Bill :Susan )
  ObjectPropertyAssertion( :loves :Susan :Jim )
  ObjectPropertyAssertion( :loves :Jim :Mary )
)

```

Conclusion:

```

Prefix( : = <http://example.org#> )
Ontology(
  Declaration( NamedIndividual( :Jack ) )
  Declaration( NamedIndividual( :John ) )
  Declaration( NamedIndividual( :Mary ) )
  Declaration( Class( :LovedLover ) )
  ClassAssertion( :LovedLover :Jack )
  ClassAssertion( :LovedLover :John )
  ClassAssertion( :LovedLover :Mary )
)

```

A.12 Test Case “12CyclicMultiRelation”

A legitimate child is a person with a father and a mother who are married. Hence, this relation is composed from a set of three different basic relations in a cyclic way. Occurrence of such relationships in a knowledge base can be indicated by instanceship in a class of legitimate children, modeled using a property chain axiom and a self-restriction. OWL 2 DL does not allow self-restrictions on composite properties.

Modeling Pattern: Heterocyclic Relationships, Section 3.12.

Premise:

```

Prefix( : = <http://example.org#> )
Ontology(
  Declaration( NamedIndividual( :Mary ) )
  Declaration( NamedIndividual( :Bill ) )
  Declaration( NamedIndividual( :John ) )
  Declaration( Class( :LegitimateChild ) )
  Declaration( ObjectProperty( :hasMother ) )
  Declaration( ObjectProperty( :hasFather ) )
  Declaration( ObjectProperty( :hasSpouse ) )
  Declaration( ObjectProperty( :z ) )
  SubObjectPropertyOf(
    ObjectPropertyChain(
      :hasMother
      :hasSpouse
    )
    ObjectInverseOf( :hasFather ) )
    :z )
  SubClassOf( ObjectHasSelf( :z ) :LegitimateChild )
  ObjectPropertyAssertion( :hasMother :John :Mary )
  ObjectPropertyAssertion( :hasFather :John :Bill )
  ObjectPropertyAssertion( :hasSpouse :Mary :Bill )
)

```

Conclusion:

```

Prefix( : = <http://example.org#> )
Ontology(
  Declaration( NamedIndividual( :John ) )
  Declaration( Class( :LegitimateChild ) )
  ClassAssertion( :LegitimateChild :John )
)

```

B Detailed Results

These are the detailed results of all the evaluations that have been conducted for OWL 2 DL reasoners (entailment tests) and FOL reasoners (entailment and satisfiability tests) using the Complex Family Relations test suite. The results are also available in electronic form in the supplementary material.

B.1 OWL 2 DL Reasoners: Entailment Checking Results

These are the detailed entailment checking results for the OWL 2 DL reasoners using the twelve entailments of the "Complex Family Relations" test suite. For each reasoner, there is a list of reasoning results, where each entry is a section telling the name of the test case, the type of the test case (always "entailment checking"), all output written by the reasoner (including error messages), the reasoning outcome, and the CPU time in milliseconds (ms). Possible reasoning outcomes are: "entailment" (correct result), "non-entailment" (wrong result), "timeout" (timeout), and "error" (error).

Fact++

```
*** -- Starting Reasoner Evaluation --
*** Reasoner: <FaCT++>
*** Testsuite: <Complex Family Relations>

*** Reasoner Warm-Up (one consistency check in advance of evaluation)...
FaCT++.Kernel: Reasoner for the SROIQ(D) Description Logic, 64-bit
Copyright (C) Dmitry Tsarkov, 2002-2011. Version 1.5.3 (7 December 2011)

*** Testcase: <01AsymmetricTransitive> (entailment checking)
org.semanticweb.owlapi.reasoner.OWLReasonerRuntimeException: Non-simple object property
'http://example.org#hasAncestor' is used as a simple one
at uk.ac.manchester.cs.factplusplus.FaCTPlusPlus.isKBConsistent(Native Method)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isConsistent(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.checkConsistency(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isEntailed(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isEntailed(Unknown Source)
at org.example.OWLAPIReasonerEvaluator.checkEntailment(OWLAPIReasonerEvaluator.java:252)
at org.example.OWLAPIReasonerEvaluator.applyTestCase(OWLAPIReasonerEvaluator.java:169)
at org.example.OWLAPIReasonerEvaluator.applyTestCaseSet(OWLAPIReasonerEvaluator.java:97)
at org.example.OWLAPIReasonerEvaluator.executeEvaluation(OWLAPIReasonerEvaluator.java:65)
at org.example.OWLAPIReasonerEvaluator.main(OWLAPIReasonerEvaluator.java:51)
*** Result: error (3 ms)

*** Testcase: <02AsymmetricChained> (entailment checking)
org.semanticweb.owlapi.reasoner.OWLReasonerRuntimeException: Non-simple object property
'http://example.org#hasUncle' is used as a simple one
at uk.ac.manchester.cs.factplusplus.FaCTPlusPlus.isKBConsistent(Native Method)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isConsistent(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.checkConsistency(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isEntailed(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isEntailed(Unknown Source)
at org.example.OWLAPIReasonerEvaluator.checkEntailment(OWLAPIReasonerEvaluator.java:252)
at org.example.OWLAPIReasonerEvaluator.applyTestCase(OWLAPIReasonerEvaluator.java:169)
at org.example.OWLAPIReasonerEvaluator.applyTestCaseSet(OWLAPIReasonerEvaluator.java:97)
at org.example.OWLAPIReasonerEvaluator.executeEvaluation(OWLAPIReasonerEvaluator.java:65)
at org.example.OWLAPIReasonerEvaluator.main(OWLAPIReasonerEvaluator.java:51)
*** Result: error (3 ms)

*** Testcase: <03DisjointTransitive> (entailment checking)
```

```

org.semanticweb.owlapi.reasoner.OWLReasonerRuntimeException: Non-simple object property
'http://example.org#hasAncestor' is used as a simple one
at uk.ac.manchester.cs.factplusplus.FaCTPlusPlus.isKBConsistent(Native Method)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isConsistent(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.checkConsistency(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isEntailed(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isEntailed(Unknown Source)
at org.example.OWLAPIReasonerEvaluator.checkEntailment(OWLAPIReasonerEvaluator.java:252)
at org.example.OWLAPIReasonerEvaluator.applyTestCase(OWLAPIReasonerEvaluator.java:169)
at org.example.OWLAPIReasonerEvaluator.applyTestCaseSet(OWLAPIReasonerEvaluator.java:97)
at org.example.OWLAPIReasonerEvaluator.executeEvaluation(OWLAPIReasonerEvaluator.java:65)
at org.example.OWLAPIReasonerEvaluator.main(OWLAPIReasonerEvaluator.java:51)
*** Result: error (3 ms)

*** Testcase: <04DisjointChained> (entailment checking)
org.semanticweb.owlapi.reasoner.OWLReasonerRuntimeException: Non-simple object property
'http://example.org#hasUncle' is used as a simple one
at uk.ac.manchester.cs.factplusplus.FaCTPlusPlus.isKBConsistent(Native Method)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isConsistent(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.checkConsistency(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isEntailed(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isEntailed(Unknown Source)
at org.example.OWLAPIReasonerEvaluator.checkEntailment(OWLAPIReasonerEvaluator.java:252)
at org.example.OWLAPIReasonerEvaluator.applyTestCase(OWLAPIReasonerEvaluator.java:169)
at org.example.OWLAPIReasonerEvaluator.applyTestCaseSet(OWLAPIReasonerEvaluator.java:97)
at org.example.OWLAPIReasonerEvaluator.executeEvaluation(OWLAPIReasonerEvaluator.java:65)
at org.example.OWLAPIReasonerEvaluator.main(OWLAPIReasonerEvaluator.java:51)
*** Result: error (3 ms)

*** Testcase: <05NumberrestrictedTransitive> (entailment checking)
org.semanticweb.owlapi.reasoner.OWLReasonerRuntimeException: Non-simple object property
'http://example.org#hasAncestor' is used as a simple one
at uk.ac.manchester.cs.factplusplus.FaCTPlusPlus.isKBConsistent(Native Method)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isConsistent(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.checkConsistency(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isEntailed(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isEntailed(Unknown Source)
at org.example.OWLAPIReasonerEvaluator.checkEntailment(OWLAPIReasonerEvaluator.java:252)
at org.example.OWLAPIReasonerEvaluator.applyTestCase(OWLAPIReasonerEvaluator.java:169)
at org.example.OWLAPIReasonerEvaluator.applyTestCaseSet(OWLAPIReasonerEvaluator.java:97)
at org.example.OWLAPIReasonerEvaluator.executeEvaluation(OWLAPIReasonerEvaluator.java:65)
at org.example.OWLAPIReasonerEvaluator.main(OWLAPIReasonerEvaluator.java:51)
*** Result: error (3 ms)

*** Testcase: <06NumberrestrictedChained> (entailment checking)
org.semanticweb.owlapi.reasoner.OWLReasonerRuntimeException: Non-simple object property
'http://example.org#hasMaternalGrandfather' is used as a simple one
at uk.ac.manchester.cs.factplusplus.FaCTPlusPlus.isKBConsistent(Native Method)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isConsistent(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.checkConsistency(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isEntailed(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isEntailed(Unknown Source)
at org.example.OWLAPIReasonerEvaluator.checkEntailment(OWLAPIReasonerEvaluator.java:252)
at org.example.OWLAPIReasonerEvaluator.applyTestCase(OWLAPIReasonerEvaluator.java:169)
at org.example.OWLAPIReasonerEvaluator.applyTestCaseSet(OWLAPIReasonerEvaluator.java:97)
at org.example.OWLAPIReasonerEvaluator.executeEvaluation(OWLAPIReasonerEvaluator.java:65)
at org.example.OWLAPIReasonerEvaluator.main(OWLAPIReasonerEvaluator.java:51)
*** Result: error (4 ms)

*** Testcase: <07NonregularSingleChained> (entailment checking)
java.lang.NoSuchMethodError: org.semanticweb.owlapi.reasoner.AxiomNotInProfileException:
method <init>(Ljava/lang/String;)V not found
at uk.ac.manchester.cs.factplusplus.FaCTPlusPlus.isKBConsistent(Native Method)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isConsistent(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.checkConsistency(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isEntailed(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isEntailed(Unknown Source)
at org.example.OWLAPIReasonerEvaluator.checkEntailment(OWLAPIReasonerEvaluator.java:252)

```

```

at org.example.OWLAPIReasonerEvaluator.applyTestCase(OWLAPIReasonerEvaluator.java:169)
at org.example.OWLAPIReasonerEvaluator.applyTestCaseSet(OWLAPIReasonerEvaluator.java:97)
at org.example.OWLAPIReasonerEvaluator.executeEvaluation(OWLAPIReasonerEvaluator.java:65)
at org.example.OWLAPIReasonerEvaluator.main(OWLAPIReasonerEvaluator.java:51)
*** Result: error (4 ms)

*** Testcase: <08NonregularMultiChained> (entailment checking)
java.lang.NoSuchMethodError: org.semanticweb.owlapi.reasoner.AxiomNotInProfileException:
method <init>(Ljava/lang/String;)V not found
at uk.ac.manchester.cs.factplusplus.FaCTPlusPlus.isKBConsistent(Native Method)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isConsistent(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.checkConsistency(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isEntailed(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isEntailed(Unknown Source)
at org.example.OWLAPIReasonerEvaluator.checkEntailment(OWLAPIReasonerEvaluator.java:252)
at org.example.OWLAPIReasonerEvaluator.applyTestCase(OWLAPIReasonerEvaluator.java:169)
at org.example.OWLAPIReasonerEvaluator.applyTestCaseSet(OWLAPIReasonerEvaluator.java:97)
at org.example.OWLAPIReasonerEvaluator.executeEvaluation(OWLAPIReasonerEvaluator.java:65)
at org.example.OWLAPIReasonerEvaluator.main(OWLAPIReasonerEvaluator.java:51)
*** Result: error (3 ms)

*** Testcase: <09ScopedEquivalence> (entailment checking)
org.semanticweb.owlapi.reasoner.OWLReasonerRuntimeException: Non-simple object property
'http://example.org#hasRelativeOrSelf' is used as a simple one
at uk.ac.manchester.cs.factplusplus.FaCTPlusPlus.isKBConsistent(Native Method)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isConsistent(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.checkConsistency(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isEntailed(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isEntailed(Unknown Source)
at org.example.OWLAPIReasonerEvaluator.checkEntailment(OWLAPIReasonerEvaluator.java:252)
at org.example.OWLAPIReasonerEvaluator.applyTestCase(OWLAPIReasonerEvaluator.java:169)
at org.example.OWLAPIReasonerEvaluator.applyTestCaseSet(OWLAPIReasonerEvaluator.java:97)
at org.example.OWLAPIReasonerEvaluator.executeEvaluation(OWLAPIReasonerEvaluator.java:65)
at org.example.OWLAPIReasonerEvaluator.main(OWLAPIReasonerEvaluator.java:51)
*** Result: error (3 ms)

*** Testcase: <10ReflexiveTransitive> (entailment checking)
org.semanticweb.owlapi.reasoner.OWLReasonerRuntimeException: Non-simple object property
'http://example.org#hasAncestorOrSelf' is used as a simple one
at uk.ac.manchester.cs.factplusplus.FaCTPlusPlus.isKBConsistent(Native Method)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isConsistent(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.checkConsistency(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isEntailed(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isEntailed(Unknown Source)
at org.example.OWLAPIReasonerEvaluator.checkEntailment(OWLAPIReasonerEvaluator.java:252)
at org.example.OWLAPIReasonerEvaluator.applyTestCase(OWLAPIReasonerEvaluator.java:169)
at org.example.OWLAPIReasonerEvaluator.applyTestCaseSet(OWLAPIReasonerEvaluator.java:97)
at org.example.OWLAPIReasonerEvaluator.executeEvaluation(OWLAPIReasonerEvaluator.java:65)
at org.example.OWLAPIReasonerEvaluator.main(OWLAPIReasonerEvaluator.java:51)
*** Result: error (3 ms)

*** Testcase: <11CyclicSingleRelation> (entailment checking)
org.semanticweb.owlapi.reasoner.OWLReasonerRuntimeException: Non-simple object property
'http://example.org#z' is used as a simple one
at uk.ac.manchester.cs.factplusplus.FaCTPlusPlus.isKBConsistent(Native Method)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isConsistent(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.checkConsistency(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isEntailed(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isEntailed(Unknown Source)
at org.example.OWLAPIReasonerEvaluator.checkEntailment(OWLAPIReasonerEvaluator.java:252)
at org.example.OWLAPIReasonerEvaluator.applyTestCase(OWLAPIReasonerEvaluator.java:169)
at org.example.OWLAPIReasonerEvaluator.applyTestCaseSet(OWLAPIReasonerEvaluator.java:97)
at org.example.OWLAPIReasonerEvaluator.executeEvaluation(OWLAPIReasonerEvaluator.java:65)
at org.example.OWLAPIReasonerEvaluator.main(OWLAPIReasonerEvaluator.java:51)
*** Result: error (4 ms)

*** Testcase: <12CyclicMultiRelation> (entailment checking)
org.semanticweb.owlapi.reasoner.OWLReasonerRuntimeException: Non-simple object property

```

```
'http://example.org#z' is used as a simple one
at uk.ac.manchester.cs.factplusplus.FaCTPlusPlus.isKBConsistent(Native Method)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isConsistent(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.checkConsistency(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isEntailed(Unknown Source)
at uk.ac.manchester.cs.factplusplus.owlapiv3.FaCTPlusPlusReasoner.isEntailed(Unknown Source)
at org.example.OWLAPIReasonerEvaluator.checkEntailment(OWLAPIReasonerEvaluator.java:252)
at org.example.OWLAPIReasonerEvaluator.applyTestCase(OWLAPIReasonerEvaluator.java:169)
at org.example.OWLAPIReasonerEvaluator.applyTestCaseSet(OWLAPIReasonerEvaluator.java:97)
at org.example.OWLAPIReasonerEvaluator.executeEvaluation(OWLAPIReasonerEvaluator.java:65)
at org.example.OWLAPIReasonerEvaluator.main(OWLAPIReasonerEvaluator.java:51)
*** Result: error (2 ms)
```

Hermit

```
*** -- Starting Reasoner Evaluation --
*** Reasoner: <Hermit>
*** Testsuite: <Complex Family Relations>

*** Reasoner Warm-Up (one consistency check in advance of evaluation)...

*** Testcase: <O1AsymmetricTransitive> (entailment checking)
java.lang.IllegalArgumentException: Non-simple property '<http://example.org#hasAncestor>'
or its inverse appears in asymmetric object property axiom.
at org.semanticweb.Hermit.structural.ObjectPropertyInclusionManager.rewriteAxioms(Unknown Source)
at org.semanticweb.Hermit.structural.OWLClausification.preprocessAndClausify(Unknown Source)
at org.semanticweb.Hermit.Reasoner.loadOntology(Unknown Source)
at org.semanticweb.Hermit.Reasoner.<init>(Unknown Source)
at org.semanticweb.Hermit.Reasoner.<init>(Unknown Source)
at org.semanticweb.Hermit.Reasoner$ReasonerFactory.createHermitOWLReasoner(Unknown Source)
at org.semanticweb.Hermit.Reasoner$ReasonerFactory.createReasoner(Unknown Source)
at org.semanticweb.Hermit.Reasoner$ReasonerFactory.createReasoner(Unknown Source)
at org.example.reasoner.HermitReasonerF.createReasoner(HermitReasonerF.java:26)
at org.example.OWLAPIReasonerEvaluator.checkEntailment(OWLAPIReasonerEvaluator.java:249)
at org.example.OWLAPIReasonerEvaluator.applyTestCase(OWLAPIReasonerEvaluator.java:170)
at org.example.OWLAPIReasonerEvaluator.applyTestCaseSet(OWLAPIReasonerEvaluator.java:98)
at org.example.OWLAPIReasonerEvaluator.executeEvaluation(OWLAPIReasonerEvaluator.java:66)
at org.example.OWLAPIReasonerEvaluator.main(OWLAPIReasonerEvaluator.java:52)
*** Result: error (25 ms)

*** Testcase: <O2AsymmetricChained> (entailment checking)
java.lang.IllegalArgumentException: Non-simple property '<http://example.org#hasUncle>'
or its inverse appears in asymmetric object property axiom.
at org.semanticweb.Hermit.structural.ObjectPropertyInclusionManager.rewriteAxioms(Unknown Source)
at org.semanticweb.Hermit.structural.OWLClausification.preprocessAndClausify(Unknown Source)
at org.semanticweb.Hermit.Reasoner.loadOntology(Unknown Source)
at org.semanticweb.Hermit.Reasoner.<init>(Unknown Source)
at org.semanticweb.Hermit.Reasoner.<init>(Unknown Source)
at org.semanticweb.Hermit.Reasoner$ReasonerFactory.createHermitOWLReasoner(Unknown Source)
at org.semanticweb.Hermit.Reasoner$ReasonerFactory.createReasoner(Unknown Source)
at org.semanticweb.Hermit.Reasoner$ReasonerFactory.createReasoner(Unknown Source)
at org.example.reasoner.HermitReasonerF.createReasoner(HermitReasonerF.java:26)
at org.example.OWLAPIReasonerEvaluator.checkEntailment(OWLAPIReasonerEvaluator.java:249)
at org.example.OWLAPIReasonerEvaluator.applyTestCase(OWLAPIReasonerEvaluator.java:170)
at org.example.OWLAPIReasonerEvaluator.applyTestCaseSet(OWLAPIReasonerEvaluator.java:98)
at org.example.OWLAPIReasonerEvaluator.executeEvaluation(OWLAPIReasonerEvaluator.java:66)
at org.example.OWLAPIReasonerEvaluator.main(OWLAPIReasonerEvaluator.java:52)
*** Result: error (4 ms)

*** Testcase: <O3DisjointTransitive> (entailment checking)
java.lang.IllegalArgumentException: Non-simple property '<http://example.org#hasAncestor>'
or its inverse appears in disjoint properties axiom.
at org.semanticweb.Hermit.structural.ObjectPropertyInclusionManager.rewriteAxioms(Unknown Source)
at org.semanticweb.Hermit.structural.OWLClausification.preprocessAndClausify(Unknown Source)
at org.semanticweb.Hermit.Reasoner.loadOntology(Unknown Source)
at org.semanticweb.Hermit.Reasoner.<init>(Unknown Source)
at org.semanticweb.Hermit.Reasoner.<init>(Unknown Source)
```

```

at org.semanticweb.HermiT.Reasoner$ReasonerFactory.createHermiTOWLReasoner(Unknown Source)
at org.semanticweb.HermiT.Reasoner$ReasonerFactory.createReasoner(Unknown Source)
at org.semanticweb.HermiT.Reasoner$ReasonerFactory.createReasoner(Unknown Source)
at org.example.reasoner.HermiTReasonerF.createReasoner(HermiTReasonerF.java:26)
at org.example.OWLAPIReasonerEvaluator.checkEntailment(OWLAPIReasonerEvaluator.java:249)
at org.example.OWLAPIReasonerEvaluator.applyTestCase(OWLAPIReasonerEvaluator.java:170)
at org.example.OWLAPIReasonerEvaluator.applyTestCaseSet(OWLAPIReasonerEvaluator.java:98)
at org.example.OWLAPIReasonerEvaluator.executeEvaluation(OWLAPIReasonerEvaluator.java:66)
at org.example.OWLAPIReasonerEvaluator.main(OWLAPIReasonerEvaluator.java:52)
*** Result: error (5 ms)

*** Testcase: <04DisjointChained> (entailment checking)
java.lang.IllegalArgumentException: Non-simple property '<http://example.org#hasUncle>'
or its inverse appears in disjoint properties axiom.
at org.semanticweb.HermiT.structural.ObjectPropertyInclusionManager.rewriteAxioms(Unknown Source)
at org.semanticweb.HermiT.structural.OWLClausification.preprocessAndClausify(Unknown Source)
at org.semanticweb.HermiT.Reasoner.loadOntology(Unknown Source)
at org.semanticweb.HermiT.Reasoner.<init>(Unknown Source)
at org.semanticweb.HermiT.Reasoner.<init>(Unknown Source)
at org.semanticweb.HermiT.Reasoner$ReasonerFactory.createHermiTOWLReasoner(Unknown Source)
at org.semanticweb.HermiT.Reasoner$ReasonerFactory.createReasoner(Unknown Source)
at org.semanticweb.HermiT.Reasoner$ReasonerFactory.createReasoner(Unknown Source)
at org.example.reasoner.HermiTReasonerF.createReasoner(HermiTReasonerF.java:26)
at org.example.OWLAPIReasonerEvaluator.checkEntailment(OWLAPIReasonerEvaluator.java:249)
at org.example.OWLAPIReasonerEvaluator.applyTestCase(OWLAPIReasonerEvaluator.java:170)
at org.example.OWLAPIReasonerEvaluator.applyTestCaseSet(OWLAPIReasonerEvaluator.java:98)
at org.example.OWLAPIReasonerEvaluator.executeEvaluation(OWLAPIReasonerEvaluator.java:66)
at org.example.OWLAPIReasonerEvaluator.main(OWLAPIReasonerEvaluator.java:52)
*** Result: error (11 ms)

*** Testcase: <05NumberrestrictedTransitive> (entailment checking)
java.lang.IllegalArgumentException: Non-simple property '<http://example.org#hasAncestor>'
or its inverse appears in the cardinality restriction
'ObjectMinCardinality(2 <http://example.org#hasAncestor> <http://example.org#Person>)'
at org.semanticweb.HermiT.structural.ObjectPropertyInclusionManager.rewriteAxioms(Unknown Source)
at org.semanticweb.HermiT.structural.OWLClausification.preprocessAndClausify(Unknown Source)
at org.semanticweb.HermiT.Reasoner.loadOntology(Unknown Source)
at org.semanticweb.HermiT.Reasoner.<init>(Unknown Source)
at org.semanticweb.HermiT.Reasoner.<init>(Unknown Source)
at org.semanticweb.HermiT.Reasoner$ReasonerFactory.createHermiTOWLReasoner(Unknown Source)
at org.semanticweb.HermiT.Reasoner$ReasonerFactory.createReasoner(Unknown Source)
at org.semanticweb.HermiT.Reasoner$ReasonerFactory.createReasoner(Unknown Source)
at org.example.reasoner.HermiTReasonerF.createReasoner(HermiTReasonerF.java:26)
at org.example.OWLAPIReasonerEvaluator.checkEntailment(OWLAPIReasonerEvaluator.java:249)
at org.example.OWLAPIReasonerEvaluator.applyTestCase(OWLAPIReasonerEvaluator.java:170)
at org.example.OWLAPIReasonerEvaluator.applyTestCaseSet(OWLAPIReasonerEvaluator.java:98)
at org.example.OWLAPIReasonerEvaluator.executeEvaluation(OWLAPIReasonerEvaluator.java:66)
at org.example.OWLAPIReasonerEvaluator.main(OWLAPIReasonerEvaluator.java:52)
*** Result: error (9 ms)

*** Testcase: <06NumberrestrictedChained> (entailment checking)
java.lang.IllegalArgumentException: Non-simple property '<http://example.org#hasMaternalGrandfather>'
or its inverse appears in the cardinality restriction
'ObjectMaxCardinality(1 <http://example.org#hasMaternalGrandfather> owl:Thing)'
at org.semanticweb.HermiT.structural.ObjectPropertyInclusionManager.rewriteAxioms(Unknown Source)
at org.semanticweb.HermiT.structural.OWLClausification.preprocessAndClausify(Unknown Source)
at org.semanticweb.HermiT.Reasoner.loadOntology(Unknown Source)
at org.semanticweb.HermiT.Reasoner.<init>(Unknown Source)
at org.semanticweb.HermiT.Reasoner.<init>(Unknown Source)
at org.semanticweb.HermiT.Reasoner$ReasonerFactory.createHermiTOWLReasoner(Unknown Source)
at org.semanticweb.HermiT.Reasoner$ReasonerFactory.createReasoner(Unknown Source)
at org.semanticweb.HermiT.Reasoner$ReasonerFactory.createReasoner(Unknown Source)
at org.example.reasoner.HermiTReasonerF.createReasoner(HermiTReasonerF.java:26)
at org.example.OWLAPIReasonerEvaluator.checkEntailment(OWLAPIReasonerEvaluator.java:249)
at org.example.OWLAPIReasonerEvaluator.applyTestCase(OWLAPIReasonerEvaluator.java:170)
at org.example.OWLAPIReasonerEvaluator.applyTestCaseSet(OWLAPIReasonerEvaluator.java:98)
at org.example.OWLAPIReasonerEvaluator.executeEvaluation(OWLAPIReasonerEvaluator.java:66)
at org.example.OWLAPIReasonerEvaluator.main(OWLAPIReasonerEvaluator.java:52)

```

*** Result: error (6 ms)

```
*** Testcase: <07NonregularSingleChained> (entailment checking)
java.lang.IllegalArgumentException: The given property hierarchy is not regular.
at org.semanticweb.HermiT.structural.ObjectPropertyInclusionManager.buildPropertyOrdering(Unknown Source)
at org.semanticweb.HermiT.structural.ObjectPropertyInclusionManager.createAutomata(Unknown Source)
at org.semanticweb.HermiT.structural.ObjectPropertyInclusionManager.<init>(Unknown Source)
at org.semanticweb.HermiT.structural.OWLClassification.preprocessAndClassify(Unknown Source)
at org.semanticweb.HermiT.Reasoner.loadOntology(Unknown Source)
at org.semanticweb.HermiT.Reasoner.<init>(Unknown Source)
at org.semanticweb.HermiT.Reasoner.<init>(Unknown Source)
at org.semanticweb.HermiT.Reasoner$ReasonerFactory.createHermiTOWLReasoner(Unknown Source)
at org.semanticweb.HermiT.Reasoner$ReasonerFactory.createReasoner(Unknown Source)
at org.semanticweb.HermiT.Reasoner$ReasonerFactory.createReasoner(Unknown Source)
at org.semanticweb.HermiT.Reasoner$ReasonerFactory.createReasoner(Unknown Source)
at org.example.reasoner.HermiTReasonerF.createReasoner(HermiTReasonerF.java:26)
at org.example.OWLAPIReasonerEvaluator.checkEntailment(OWLAPIReasonerEvaluator.java:249)
at org.example.OWLAPIReasonerEvaluator.applyTestCase(OWLAPIReasonerEvaluator.java:170)
at org.example.OWLAPIReasonerEvaluator.applyTestCaseSet(OWLAPIReasonerEvaluator.java:98)
at org.example.OWLAPIReasonerEvaluator.executeEvaluation(OWLAPIReasonerEvaluator.java:66)
at org.example.OWLAPIReasonerEvaluator.main(OWLAPIReasonerEvaluator.java:52)
*** Result: error (2 ms)
```

```
*** Testcase: <08NonregularMultiChained> (entailment checking)
java.lang.IllegalArgumentException: The given property hierarchy is not regular.
There is a cyclic dependency involving property <http://example.org#hasCousin>
at org.semanticweb.HermiT.structural.ObjectPropertyInclusionManager.checkForRegularity(Unknown Source)
at org.semanticweb.HermiT.structural.ObjectPropertyInclusionManager.createAutomata(Unknown Source)
at org.semanticweb.HermiT.structural.ObjectPropertyInclusionManager.<init>(Unknown Source)
at org.semanticweb.HermiT.structural.OWLClassification.preprocessAndClassify(Unknown Source)
at org.semanticweb.HermiT.Reasoner.loadOntology(Unknown Source)
at org.semanticweb.HermiT.Reasoner.<init>(Unknown Source)
at org.semanticweb.HermiT.Reasoner.<init>(Unknown Source)
at org.semanticweb.HermiT.Reasoner$ReasonerFactory.createHermiTOWLReasoner(Unknown Source)
at org.semanticweb.HermiT.Reasoner$ReasonerFactory.createReasoner(Unknown Source)
at org.semanticweb.HermiT.Reasoner$ReasonerFactory.createReasoner(Unknown Source)
at org.semanticweb.HermiT.Reasoner$ReasonerFactory.createReasoner(Unknown Source)
at org.example.reasoner.HermiTReasonerF.createReasoner(HermiTReasonerF.java:26)
at org.example.OWLAPIReasonerEvaluator.checkEntailment(OWLAPIReasonerEvaluator.java:249)
at org.example.OWLAPIReasonerEvaluator.applyTestCase(OWLAPIReasonerEvaluator.java:170)
at org.example.OWLAPIReasonerEvaluator.applyTestCaseSet(OWLAPIReasonerEvaluator.java:98)
at org.example.OWLAPIReasonerEvaluator.executeEvaluation(OWLAPIReasonerEvaluator.java:66)
at org.example.OWLAPIReasonerEvaluator.main(OWLAPIReasonerEvaluator.java:52)
*** Result: error (2 ms)
```

```
*** Testcase: <09ScopedEquivalence> (entailment checking)
java.lang.IllegalArgumentException: Non-simple property '<http://example.org#hasRelativeOrSelf>'
or its inverse appears in the Self restriction 'ObjectHasSelf(<http://example.org#hasRelativeOrSelf>)' .
at org.semanticweb.HermiT.structural.ObjectPropertyInclusionManager.rewriteAxioms(Unknown Source)
at org.semanticweb.HermiT.structural.OWLClassification.preprocessAndClassify(Unknown Source)
at org.semanticweb.HermiT.Reasoner.loadOntology(Unknown Source)
at org.semanticweb.HermiT.Reasoner.<init>(Unknown Source)
at org.semanticweb.HermiT.Reasoner.<init>(Unknown Source)
at org.semanticweb.HermiT.Reasoner$ReasonerFactory.createHermiTOWLReasoner(Unknown Source)
at org.semanticweb.HermiT.Reasoner$ReasonerFactory.createReasoner(Unknown Source)
at org.semanticweb.HermiT.Reasoner$ReasonerFactory.createReasoner(Unknown Source)
at org.semanticweb.HermiT.Reasoner$ReasonerFactory.createReasoner(Unknown Source)
at org.example.reasoner.HermiTReasonerF.createReasoner(HermiTReasonerF.java:26)
at org.example.OWLAPIReasonerEvaluator.checkEntailment(OWLAPIReasonerEvaluator.java:249)
at org.example.OWLAPIReasonerEvaluator.applyTestCase(OWLAPIReasonerEvaluator.java:170)
at org.example.OWLAPIReasonerEvaluator.applyTestCaseSet(OWLAPIReasonerEvaluator.java:98)
at org.example.OWLAPIReasonerEvaluator.executeEvaluation(OWLAPIReasonerEvaluator.java:66)
at org.example.OWLAPIReasonerEvaluator.main(OWLAPIReasonerEvaluator.java:52)
*** Result: error (13 ms)
```

```
*** Testcase: <10ReflexiveTransitive> (entailment checking)
java.lang.IllegalArgumentException: Non-simple property '<http://example.org#hasAncestorOrSelf>'
or its inverse appears in the Self restriction 'ObjectHasSelf(<http://example.org#hasAncestorOrSelf>)' .
at org.semanticweb.HermiT.structural.ObjectPropertyInclusionManager.rewriteAxioms(Unknown Source)
at org.semanticweb.HermiT.structural.OWLClassification.preprocessAndClassify(Unknown Source)
at org.semanticweb.HermiT.Reasoner.loadOntology(Unknown Source)
```



```

at org.semanticweb.HermiT.Reasoner.<init>(Unknown Source)
at org.semanticweb.HermiT.Reasoner.<init>(Unknown Source)
at org.semanticweb.HermiT.Reasoner$ReasonerFactory.createHermiTOWLReasoner(Unknown Source)
at org.semanticweb.HermiT.Reasoner$ReasonerFactory.createReasoner(Unknown Source)
at org.semanticweb.HermiT.Reasoner$ReasonerFactory.createReasoner(Unknown Source)
at org.example.reasoner.HermiTReasonerF.createReasoner(HermiTReasonerF.java:26)
at org.example.OWLAPIReasonerEvaluator.checkEntailment(OWLAPIReasonerEvaluator.java:249)
at org.example.OWLAPIReasonerEvaluator.applyTestCase(OWLAPIReasonerEvaluator.java:170)
at org.example.OWLAPIReasonerEvaluator.applyTestCaseSet(OWLAPIReasonerEvaluator.java:98)
at org.example.OWLAPIReasonerEvaluator.executeEvaluation(OWLAPIReasonerEvaluator.java:66)
at org.example.OWLAPIReasonerEvaluator.main(OWLAPIReasonerEvaluator.java:52)
*** Result: error (4 ms)

*** Testcase: <11CyclicSingleRelation> (entailment checking)
*** Result: non-entailment (79 ms)

*** Testcase: <12CyclicMultiRelation> (entailment checking)
*** Result: non-entailment (15 ms)

```

Pellet

```

*** -- Starting Reasoner Evaluation --
*** Reasoner: <Pellet>
*** Testsuite: <Complex Family Relations>

*** Reasoner Warm-Up (one consistency check in advance of evaluation)...

*** Testcase: <01AsymmetricTransitive> (entailment checking)
Jun 03, 2012 4:13:42 PM com.clarkparsia.pellet.owlapiv3.PelletVisitor addUnsupportedAxiom
Warnung: Ignoring unsupported axiom: TransitiveObjectProperty(<http://example.org#hasAncestor>)
Jun 03, 2012 4:13:42 PM org.mindswap.pellet.RBox ignoreTransitivity
Warnung: Unsupported axiom: Ignoring transitivity and/or complex subproperty axioms for hasAncestor
*** Result: non-entailment (90 ms)

*** Testcase: <02AsymmetricChained> (entailment checking)
Jun 03, 2012 4:13:43 PM com.clarkparsia.pellet.owlapiv3.PelletVisitor addUnsupportedAxiom
Warnung: Ignoring unsupported axiom: SubObjectPropertyOf(ObjectPropertyChain(
  <http://example.org#hasParent> <http://example.org#hasBrother> ) <http://example.org#hasUncle>)
Jun 03, 2012 4:13:43 PM org.mindswap.pellet.RBox ignoreTransitivity
Warnung: Unsupported axiom: Ignoring transitivity and/or complex subproperty axioms for hasUncle
*** Result: non-entailment (20 ms)

*** Testcase: <03DisjointTransitive> (entailment checking)
Jun 03, 2012 4:13:43 PM com.clarkparsia.pellet.owlapiv3.PelletVisitor addUnsupportedAxiom
Warnung: Ignoring unsupported axiom: TransitiveObjectProperty(<http://example.org#hasDescendant>)
Jun 03, 2012 4:13:43 PM com.clarkparsia.pellet.owlapiv3.PelletVisitor addUnsupportedAxiom
Warnung: Ignoring unsupported axiom: TransitiveObjectProperty(<http://example.org#hasAncestor>)
Jun 03, 2012 4:13:43 PM org.mindswap.pellet.RBox ignoreTransitivity
Warnung: Unsupported axiom: Ignoring transitivity and/or complex subproperty axioms for hasAncestor
Jun 03, 2012 4:13:43 PM org.mindswap.pellet.RBox ignoreTransitivity
Warnung: Unsupported axiom: Ignoring transitivity and/or complex subproperty axioms for hasDescendant
*** Result: non-entailment (16 ms)

*** Testcase: <04DisjointChained> (entailment checking)
*** Result: non-entailment (11 ms)

*** Testcase: <05NumberrestrictedTransitive> (entailment checking)
Jun 03, 2012 4:13:43 PM com.clarkparsia.pellet.owlapiv3.PelletVisitor addUnsupportedAxiom
Warnung: Ignoring unsupported axiom: SubObjectPropertyOf(ObjectPropertyChain(
  <http://example.org#hasParent> <http://example.org#hasBrother> ) <http://example.org#hasUncle>)
Jun 03, 2012 4:13:43 PM org.mindswap.pellet.RBox ignoreTransitivity
Warnung: Unsupported axiom: Ignoring transitivity and/or complex subproperty axioms for hasUncle
Jun 03, 2012 4:13:43 PM com.clarkparsia.pellet.owlapiv3.PelletVisitor addUnsupportedAxiom
Warnung: Ignoring unsupported axiom: TransitiveObjectProperty(<http://example.org#hasAncestor>)
Jun 03, 2012 4:13:43 PM org.mindswap.pellet.RBox ignoreTransitivity
Warnung: Unsupported axiom: Ignoring transitivity and/or complex subproperty axioms for hasAncestor
*** Result: non-entailment (122 ms)

```

```

*** Testcase: <06NumberrestrictedChained> (entailment checking)
*** Result: non-entailment (9 ms)

*** Testcase: <07NonregularSingleChained> (entailment checking)
Jun 03, 2012 4:13:43 PM com.clarkparsia.pellet.owlapiv3.PelletVisitor addUnsupportedAxiom
Warnung: Ignoring unsupported axiom: SubObjectPropertyOf(ObjectPropertyChain(
  <http://example.org#hasMother> <http://example.org#hasFather> ) <http://example.org#hasMaternalGrandfather>)
Jun 03, 2012 4:13:43 PM org.mindswap.pellet.RBox ignoreTransitivity
Warnung: Unsupported axiom: Ignoring transitivity and/or complex subproperty axioms for hasMaternalGrandfather
Jun 03, 2012 4:13:43 PM org.mindswap.pellet.FSMBuildBuilder build
Warnung: Cycle detected in the complex subproperty chain involving hasRelative
Jun 03, 2012 4:13:43 PM org.mindswap.pellet.RBox ignoreTransitivity
Warnung: Unsupported axiom: Ignoring transitivity and/or complex subproperty axioms for hasRelative
*** Result: non-entailment (18 ms)

*** Testcase: <08NonregularMultiChained> (entailment checking)
Jun 03, 2012 4:13:43 PM org.mindswap.pellet.FSMBuildBuilder build
Warnung: Cycle detected in the complex subproperty chain involving inv(hasUncle)
Jun 03, 2012 4:13:43 PM org.mindswap.pellet.RBox ignoreTransitivity
Warnung: Unsupported axiom: Ignoring transitivity and/or complex subproperty axioms for hasUncle
Jun 03, 2012 4:13:43 PM org.mindswap.pellet.FSMBuildBuilder build
Warnung: Cycle detected in the complex subproperty chain involving inv(hasCousin)
Jun 03, 2012 4:13:43 PM org.mindswap.pellet.RBox ignoreTransitivity
Warnung: Unsupported axiom: Ignoring transitivity and/or complex subproperty axioms for hasCousin
*** Result: non-entailment (14 ms)

*** Testcase: <09ScopedEquivalence> (entailment checking)
Jun 03, 2012 4:13:43 PM com.clarkparsia.pellet.owlapiv3.PelletVisitor addUnsupportedAxiom
Warnung: Ignoring unsupported axiom: TransitiveObjectProperty(<http://example.org#hasRelativeOrSelf>)
Jun 03, 2012 4:13:43 PM org.mindswap.pellet.RBox ignoreTransitivity
Warnung: Unsupported axiom: Ignoring transitivity and/or complex subproperty axioms for hasRelativeOrSelf
*** Result: non-entailment (18 ms)

*** Testcase: <10ReflexiveTransitive> (entailment checking)
Jun 03, 2012 4:13:43 PM com.clarkparsia.pellet.owlapiv3.PelletVisitor addUnsupportedAxiom
Warnung: Ignoring unsupported axiom: TransitiveObjectProperty(<http://example.org#hasAncestorOrSelf>)
Jun 03, 2012 4:13:43 PM org.mindswap.pellet.RBox ignoreTransitivity
Warnung: Unsupported axiom: Ignoring transitivity and/or complex subproperty axioms for hasAncestorOrSelf
*** Result: non-entailment (11 ms)

*** Testcase: <11CyclicSingleRelation> (entailment checking)
Jun 03, 2012 4:13:43 PM com.clarkparsia.pellet.owlapiv3.PelletVisitor addUnsupportedAxiom
Warnung: Ignoring unsupported axiom: TransitiveObjectProperty(<http://example.org#z>)
Jun 03, 2012 4:13:43 PM org.mindswap.pellet.RBox ignoreTransitivity
Warnung: Unsupported axiom: Ignoring transitivity and/or complex subproperty axioms for z
org.semanticweb.owlapi.reasoner.InconsistentOntologyException: Inconsistent ontology
at com.clarkparsia.pellet.owlapiv3.PelletReasoner.convert(PelletReasoner.java:360)
at com.clarkparsia.pellet.owlapiv3.PelletReasoner.isEntailed(PelletReasoner.java:874)
at org.example.OWLAPIReasonerEvaluator.checkEntailment(OWLAPIReasonerEvaluator.java:254)
at org.example.OWLAPIReasonerEvaluator.applyTestCase(OWLAPIReasonerEvaluator.java:171)
at org.example.OWLAPIReasonerEvaluator.applyTestCaseSet(OWLAPIReasonerEvaluator.java:99)
at org.example.OWLAPIReasonerEvaluator.executeEvaluation(OWLAPIReasonerEvaluator.java:67)
at org.example.OWLAPIReasonerEvaluator.main(OWLAPIReasonerEvaluator.java:53)
*** Result: error (16 ms)

*** Testcase: <12CyclicMultiRelation> (entailment checking)
Jun 03, 2012 4:13:43 PM com.clarkparsia.pellet.owlapiv3.PelletVisitor addUnsupportedAxiom
Warnung: Ignoring unsupported axiom: SubObjectPropertyOf(ObjectPropertyChain(
  <http://example.org#hasMother> <http://example.org#hasSpouse>
  InverseOf(<http://example.org#hasFather>) ) <http://example.org#z>)
Jun 03, 2012 4:13:43 PM org.mindswap.pellet.RBox ignoreTransitivity
Warnung: Unsupported axiom: Ignoring transitivity and/or complex subproperty axioms for z
*** Result: non-entailment (23 ms)

```

B.2 FOL Reasoners: Entailment Checking Results

These are the detailed entailment checking results for the FOL reasoning systems using the twelve entailments of the "Complex Family Relations" test suite. Both theorem provers and model finders were tested. For each reasoner, there is a list of reasoning results, where each entry is a line telling the number of the test case, the name of the reasoner, the version of the reasoner, the reasoning outcome, and the CPU time in seconds. Possible reasoning outcomes are: "Theorem" (correct result), "CounterSatisfiable" (wrong result), "Timeout" (timeout), and "Error" (error; other error messages are possible).

E

```
01: % RESULT: SOT_IuG628 - E---1.5 says Theorem - CPU = 0.00
02: % RESULT: SOT_RDJyQv - E---1.5 says Theorem - CPU = 0.00
03: % RESULT: SOT_tXpe0x - E---1.5 says Theorem - CPU = 0.00
04: % RESULT: SOT_oBrUJW - E---1.5 says Theorem - CPU = 0.00
05: % RESULT: SOT_ifFa0I - E---1.5 says Theorem - CPU = 0.00
06: % RESULT: SOT_NAMN9G - E---1.5 says Theorem - CPU = 0.00
07: % RESULT: SOT_GdQLy_ - E---1.5 says Theorem - CPU = 0.00
08: % RESULT: SOT_UpcwQb - E---1.5 says Theorem - CPU = 0.00
09: % RESULT: SOT_U6z2LZ - E---1.5 says Theorem - CPU = 0.00
10: % RESULT: SOT_5KC2Z_ - E---1.5 says Theorem - CPU = 0.00
11: % RESULT: SOT_qiV0fh - E---1.5 says Theorem - CPU = 0.00
12: % RESULT: SOT_eXCCFS - E---1.5 says Theorem - CPU = 0.00
```

iProver

```
01: % RESULT: SOT_IuG628 - iProver---0.9.2 says Theorem - CPU = 0.01
02: % RESULT: SOT_RDJyQv - iProver---0.9.2 says Theorem - CPU = 0.02
03: % RESULT: SOT_tXpe0x - iProver---0.9.2 says Theorem - CPU = 0.01
04: % RESULT: SOT_oBrUJW - iProver---0.9.2 says Theorem - CPU = 0.01
05: % RESULT: SOT_ifFa0I - iProver---0.9.2 says Theorem - CPU = 0.03
06: % RESULT: SOT_NAMN9G - iProver---0.9.2 says Theorem - CPU = 0.01
07: % RESULT: SOT_GdQLy_ - iProver---0.9.2 says Theorem - CPU = 0.01
08: % RESULT: SOT_UpcwQb - iProver---0.9.2 says Theorem - CPU = 0.01
09: % RESULT: SOT_U6z2LZ - iProver---0.9.2 says Theorem - CPU = 0.01
10: % RESULT: SOT_5KC2Z_ - iProver---0.9.2 says Theorem - CPU = 0.01
11: % RESULT: SOT_qiV0fh - iProver---0.9.2 says Theorem - CPU = 0.01
12: % RESULT: SOT_eXCCFS - iProver---0.9.2 says Theorem - CPU = 0.01
```

SPASS

```
01: % RESULT: SOT_IuG628 - SPASS---3.5 says Theorem - CPU = 0.03
02: % RESULT: SOT_RDJyQv - SPASS---3.5 says Theorem - CPU = 0.02
03: % RESULT: SOT_tXpe0x - SPASS---3.5 says Theorem - CPU = 0.03
04: % RESULT: SOT_oBrUJW - SPASS---3.5 says Theorem - CPU = 0.02
05: % RESULT: SOT_ifFa0I - SPASS---3.5 says Theorem - CPU = 0.03
06: % RESULT: SOT_NAMN9G - SPASS---3.5 says Theorem - CPU = 0.02
07: % RESULT: SOT_GdQLy_ - SPASS---3.5 says Theorem - CPU = 0.03
08: % RESULT: SOT_UpcwQb - SPASS---3.5 says Theorem - CPU = 0.02
09: % RESULT: SOT_U6z2LZ - SPASS---3.5 says Theorem - CPU = 0.02
10: % RESULT: SOT_5KC2Z_ - SPASS---3.5 says Theorem - CPU = 0.03
11: % RESULT: SOT_qiV0fh - SPASS---3.5 says Theorem - CPU = 0.02
12: % RESULT: SOT_eXCCFS - SPASS---3.5 says Theorem - CPU = 0.02
```

Vampire

```

01: % RESULT: SOT_IuG628 - Vampire---2.5 says Theorem - CPU = 0.00
02: % RESULT: SOT_RDJyQv - Vampire---2.5 says Theorem - CPU = 0.00
03: % RESULT: SOT_tXpe0x - Vampire---2.5 says Theorem - CPU = 0.00
04: % RESULT: SOT_oBrUJW - Vampire---2.5 says Theorem - CPU = 0.00
05: % RESULT: SOT_1fFaOI - Vampire---2.5 says Theorem - CPU = 0.00
06: % RESULT: SOT_NAMN9G - Vampire---2.5 says Theorem - CPU = 0.00
07: % RESULT: SOT_GdQLy_ - Vampire---2.5 says Theorem - CPU = 0.00
08: % RESULT: SOT_UpcwQb - Vampire---2.5 says Theorem - CPU = 0.00
09: % RESULT: SOT_U6z2LZ - Vampire---2.5 says Theorem - CPU = 0.00
10: % RESULT: SOT_5KC2Z_ - Vampire---2.5 says Theorem - CPU = 0.00
11: % RESULT: SOT_qiV0fh - Vampire---2.5 says Theorem - CPU = 0.00
12: % RESULT: SOT_eXCCFS - Vampire---2.5 says Theorem - CPU = 0.00

```

DarwinFM

```

01: % RESULT: SOT_IuG628 - DarwinFM---1.4.5 says Theorem - CPU = 0.00
02: % RESULT: SOT_RDJyQv - DarwinFM---1.4.5 says Theorem - CPU = 0.00
03: % RESULT: SOT_tXpe0x - DarwinFM---1.4.5 says Theorem - CPU = 0.00
04: % RESULT: SOT_oBrUJW - DarwinFM---1.4.5 says Theorem - CPU = 0.00
05: % RESULT: SOT_1fFaOI - DarwinFM---1.4.5 says Timeout - CPU = 300.24
06: % RESULT: SOT_NAMN9G - DarwinFM---1.4.5 says Theorem - CPU = 0.00
07: % RESULT: SOT_GdQLy_ - DarwinFM---1.4.5 says Theorem - CPU = 0.00
08: % RESULT: SOT_UpcwQb - DarwinFM---1.4.5 says Theorem - CPU = 0.00
09: % RESULT: SOT_U6z2LZ - DarwinFM---1.4.5 says Theorem - CPU = 0.02
10: % RESULT: SOT_5KC2Z_ - DarwinFM---1.4.5 says Theorem - CPU = 0.01
11: % RESULT: SOT_qiV0fh - DarwinFM---1.4.5 says Theorem - CPU = 0.26
12: % RESULT: SOT_eXCCFS - DarwinFM---1.4.5 says Theorem - CPU = 0.00

```

Paradox

```

01: % RESULT: SOT_IuG628 - Paradox---4.0 says Theorem - CPU = 0.00
02: % RESULT: SOT_RDJyQv - Paradox---4.0 says Theorem - CPU = 0.00
03: % RESULT: SOT_tXpe0x - Paradox---4.0 says Theorem - CPU = 0.00
04: % RESULT: SOT_oBrUJW - Paradox---4.0 says Theorem - CPU = 0.00
05: % RESULT: SOT_1fFaOI - Paradox---4.0 says Timeout - CPU = 301.08
06: % RESULT: SOT_NAMN9G - Paradox---4.0 says Theorem - CPU = 0.00
07: % RESULT: SOT_GdQLy_ - Paradox---4.0 says Theorem - CPU = 0.00
08: % RESULT: SOT_UpcwQb - Paradox---4.0 says Theorem - CPU = 0.00
09: % RESULT: SOT_U6z2LZ - Paradox---4.0 says Theorem - CPU = 0.01
10: % RESULT: SOT_5KC2Z_ - Paradox---4.0 says Theorem - CPU = 0.02
11: % RESULT: SOT_qiV0fh - Paradox---4.0 says Theorem - CPU = 0.02
12: % RESULT: SOT_eXCCFS - Paradox---4.0 says Theorem - CPU = 0.00

```

B.3 FOL Reasoners: Satisfiability Checking Results

These are the detailed satisfiability checking results for the FOL reasoning systems using the twelve premise ontologies of the "Complex Family Relations" test suite. Both theorem provers and model finders were tested. For each reasoner, there is a list of reasoning results, where each entry is a line telling the number of the test case, the name of the reasoner, the version of the reasoner, the reasoning outcome, and the CPU time in seconds. Possible reasoning outcomes are: "Satisfiable" (correct result), "Unsatisfiable" (wrong result), "Timeout" (timeout), and "Error" (error; other error messages are possible).

E

```

01: % RESULT: SOT_Lx5kEN - E---1.5 says Satisfiable - CPU = 0.00
02: % RESULT: SOT_Fy6ZbS - E---1.5 says Satisfiable - CPU = 0.00
03: % RESULT: SOT_lStE3s - E---1.5 says Satisfiable - CPU = 0.00
04: % RESULT: SOT_oWiW_Y - E---1.5 says Satisfiable - CPU = 0.00
05: % RESULT: SOT_h1Sp36 - E---1.5 says Timeout - CPU = 300.06
06: % RESULT: SOT_3CuPB6 - E---1.5 says Satisfiable - CPU = 0.00
07: % RESULT: SOT_SzYUiL - E---1.5 says Satisfiable - CPU = 0.00
08: % RESULT: SOT_L6XtBx - E---1.5 says Satisfiable - CPU = 0.00
09: % RESULT: SOT_IfyAM_ - E---1.5 says Satisfiable - CPU = 0.00
10: % RESULT: SOT_e2Dpg6 - E---1.5 says Satisfiable - CPU = 0.00
11: % RESULT: SOT_bIt8nh - E---1.5 says Satisfiable - CPU = 2.07
12: % RESULT: SOT_F6n_IG - E---1.5 says Satisfiable - CPU = 0.00

```

iProver

```

01: % RESULT: SOT_Lx5kEN - iProver---0.9.2 says Satisfiable - CPU = 0.02
02: % RESULT: SOT_Fy6ZbS - iProver---0.9.2 says Satisfiable - CPU = 0.01
03: % RESULT: SOT_lStE3s - iProver---0.9.2 says Satisfiable - CPU = 0.01
04: % RESULT: SOT_oWiW_Y - iProver---0.9.2 says Satisfiable - CPU = 0.02
05: % RESULT: SOT_h1Sp36 - iProver---0.9.2 says Satisfiable - CPU = 0.29
06: % RESULT: SOT_3CuPB6 - iProver---0.9.2 says Satisfiable - CPU = 0.01
07: % RESULT: SOT_SzYUiL - iProver---0.9.2 says Satisfiable - CPU = 0.01
08: % RESULT: SOT_L6XtBx - iProver---0.9.2 says Satisfiable - CPU = 0.02
09: % RESULT: SOT_IfyAM_ - iProver---0.9.2 says Satisfiable - CPU = 0.01
10: % RESULT: SOT_e2Dpg6 - iProver---0.9.2 says Satisfiable - CPU = 0.01
11: % RESULT: SOT_bIt8nh - iProver---0.9.2 says Satisfiable - CPU = 0.01
12: % RESULT: SOT_F6n_IG - iProver---0.9.2 says Satisfiable - CPU = 0.01

```

SPASS

```

01: % RESULT: SOT_Lx5kEN - SPASS---3.5 says Satisfiable - CPU = 0.02
02: % RESULT: SOT_Fy6ZbS - SPASS---3.5 says Satisfiable - CPU = 0.02
03: % RESULT: SOT_lStE3s - SPASS---3.5 says Satisfiable - CPU = 0.03
04: % RESULT: SOT_oWiW_Y - SPASS---3.5 says Satisfiable - CPU = 0.03
05: % RESULT: SOT_h1Sp36 - SPASS---3.5 says Timeout - CPU = 300.77
06: % RESULT: SOT_3CuPB6 - SPASS---3.5 says Satisfiable - CPU = 0.03
07: % RESULT: SOT_SzYUiL - SPASS---3.5 says Satisfiable - CPU = 0.03
08: % RESULT: SOT_L6XtBx - SPASS---3.5 says Satisfiable - CPU = 0.03
09: % RESULT: SOT_IfyAM_ - SPASS---3.5 says Satisfiable - CPU = 0.02
10: % RESULT: SOT_e2Dpg6 - SPASS---3.5 says Satisfiable - CPU = 0.03
11: % RESULT: SOT_bIt8nh - SPASS---3.5 says Satisfiable - CPU = 0.03
12: % RESULT: SOT_F6n_IG - SPASS---3.5 says Satisfiable - CPU = 0.02

```

Vampire

```

01: % RESULT: SOT_Lx5kEN - Vampire---2.5 says Satisfiable - CPU = 28.19
02: % RESULT: SOT_Fy6ZbS - Vampire---2.5 says Satisfiable - CPU = 0.00
03: % RESULT: SOT_lStE3s - Vampire---2.5 says Satisfiable - CPU = 28.00
04: % RESULT: SOT_oWiW_Y - Vampire---2.5 says Satisfiable - CPU = 0.00
05: % RESULT: SOT_h1Sp36 - Vampire---2.5 says Timeout - CPU = 300.02
06: % RESULT: SOT_3CuPB6 - Vampire---2.5 says Satisfiable - CPU = 86.83
07: % RESULT: SOT_SzYUiL - Vampire---2.5 says Satisfiable - CPU = 0.00
08: % RESULT: SOT_L6XtBx - Vampire---2.5 says Satisfiable - CPU = 0.00
09: % RESULT: SOT_IfyAM_ - Vampire---2.5 says Satisfiable - CPU = 0.00
10: % RESULT: SOT_e2Dpg6 - Vampire---2.5 says Satisfiable - CPU = 28.19
11: % RESULT: SOT_bIt8nh - Vampire---2.5 says Satisfiable - CPU = 28.21
12: % RESULT: SOT_F6n_IG - Vampire---2.5 says Satisfiable - CPU = 0.00

```

DarwinFM

```

01: % RESULT: SOT_Lx5kEN - DarwinFM---1.4.5 says Satisfiable - CPU = 0.00
02: % RESULT: SOT_Fy6ZbS - DarwinFM---1.4.5 says Satisfiable - CPU = 0.00
03: % RESULT: SOT_lStE3s - DarwinFM---1.4.5 says Satisfiable - CPU = 0.00
04: % RESULT: SOT_oWiW_Y - DarwinFM---1.4.5 says Satisfiable - CPU = 0.00
05: % RESULT: SOT_h1Sp36 - DarwinFM---1.4.5 says Satisfiable - CPU = 0.00
06: % RESULT: SOT_3CuPB6 - DarwinFM---1.4.5 says Satisfiable - CPU = 0.00
07: % RESULT: SOT_SzYUiL - DarwinFM---1.4.5 says Satisfiable - CPU = 0.00
08: % RESULT: SOT_L6XtBx - DarwinFM---1.4.5 says Satisfiable - CPU = 0.00
09: % RESULT: SOT_IfyAM_ - DarwinFM---1.4.5 says Satisfiable - CPU = 0.00
10: % RESULT: SOT_e2Dpg6 - DarwinFM---1.4.5 says Satisfiable - CPU = 0.00
11: % RESULT: SOT_bIt8nh - DarwinFM---1.4.5 says Satisfiable - CPU = 0.00
12: % RESULT: SOT_F6n_IG - DarwinFM---1.4.5 says Satisfiable - CPU = 0.00

```

Paradox

```

01: % RESULT: SOT_Lx5kEN - Paradox---4.0 says Satisfiable - CPU = 0.00
02: % RESULT: SOT_Fy6ZbS - Paradox---4.0 says Satisfiable - CPU = 0.00
03: % RESULT: SOT_lStE3s - Paradox---4.0 says Satisfiable - CPU = 0.00
04: % RESULT: SOT_oWiW_Y - Paradox---4.0 says Satisfiable - CPU = 0.00
05: % RESULT: SOT_h1Sp36 - Paradox---4.0 says Satisfiable - CPU = 0.00
06: % RESULT: SOT_3CuPB6 - Paradox---4.0 says Satisfiable - CPU = 0.00
07: % RESULT: SOT_SzYUiL - Paradox---4.0 says Satisfiable - CPU = 0.00
08: % RESULT: SOT_L6XtBx - Paradox---4.0 says Satisfiable - CPU = 0.04
09: % RESULT: SOT_IfyAM_ - Paradox---4.0 says Satisfiable - CPU = 0.00
10: % RESULT: SOT_e2Dpg6 - Paradox---4.0 says Satisfiable - CPU = 0.00
11: % RESULT: SOT_bIt8nh - Paradox---4.0 says Satisfiable - CPU = 0.01
12: % RESULT: SOT_F6n_IG - Paradox---4.0 says Satisfiable - CPU = 0.00

```

C Tool for Translating OWL 2 Ontologies into TPTP

In this section, we give an overview to our tool for translating OWL 2 ontologies into FOL (TPTP), which implements the approach given in Section 5.2, and which was used in the evaluation in Section 5.3. The executable tool and its source code are available in electronical form in the supplementary material.

owldirect2tptp: A tool to translate OWL 2 ontologies or queries into TPTP-style FOL formulae according to the OWL 2 Direct Semantics. 2012 by Michael Schneider <schneid@fzi.de>

USAGE:

```
java -jar owldirect2tptp.jar <Command> [<Options>...]
  * plain <OntologyLoc> <OutputLoc> [<Semantics>]
  * axiom <OntologyLoc> <FormulaName> <OutputLoc> [<Semantics>]
  * conjecture <OntologyLoc> <FormulaName> <OutputLoc> [<Semantics>]
  * question <OntologyLoc> <FormulaName> <OutputLoc> [<Semantics>]
  * check-unsupported <OntologyLoc> [<Semantics>]
```

All ontologies are read from the specified input locations. The input format can be any valid OWL 2 encoding (e.g. OWL 2 Functional Syntax, RDF/XML, or Manchester Syntax). The resulting TPTP formulae will have the formula names that are specified as arguments. The result is written into a single document, for which the output location is defined as an argument. The semantics underlying the translation into FOL can be optionally defined as either the standard first-order-based OWL 2 Direct Semantics ('standard') or a HiLog-style variant of it ('hilog'). The default semantics is 'standard'.

If an unsupported language construct is being used in an axiom of an ontology, the axiom is ignored by the translation. Use the command 'check-unsupported' to find out whether an ontology contains any unsupported features, in which case the return value will not be 0 and a list of messages is printed indicating the issues.

For more details on the translation as well as on current limitations, see the description of package `org.swertia.plugins.translation.standard.owldirect.essentials.translation.tptp`.

Note: To avoid out-of-memory errors when translating large ontologies, set the heap space of the Java runtime environment to a sufficient size via option '-Xms' (e.g. 'java -Xms1500M' for 1.5GB RAM).